PROGRESSIVE OVERPRINTING OF NORMAL FAULT SYSTEMS AND THEIR ROLE IN TERTIARY EXHUMATION OF THE EAST HUMBOLDT-WOOD HILLS METAMORPHIC COMPLEX NORTHEAST NEVADA

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ABSTRACT. Low- and high-angle, normal-sense faults present along the northern margin of the East Humboldt-Wood Hills metamorphic complex record a protracted history of episodic extensional unroofing. The earliest extension associated with the exhumation of the metamorphic complex occurred in the mid-Eocene (about 50 Ma) during slip along the west-rooted Wells Peak fault. Subsequent extension developed during movement along the east-rooted Black Mountain fault system in the late Eocene (about 35 Ma). Continued exhumation of the high-grade metamorphic rocks, occurred during the late Oligocene to early Miocene (about 29-23 Ma) along a west-rooted, normal-sense, plastic-to-brittle shear zone exposed along the length of the East Humboldt Range and much of the Ruby Mountains. The mylonitic shear zone, Wells Peak fault, and Black Mountain fault system were all overprinted by the west-rooted, low- to high-angle Mary’s River fault system which was active from mid-Miocene to Holocene. Broadly coeval extension in the Windermere Hills was also accomplished by the development of high-angle, north and east dipping normal faults between approximately 35-12 Ma and 12-10 Ma.

INTRODUCTION

The exhumation of metamorphic core complexes in the North American Cordillera is largely related to highly localized upper to mid-crustal extension during the Tertiary [e.g., Dokka et al., 1986; Reynolds et al., 1986; Davis, 1988], although Mesozoic extension may play a significant role in the development of some complexes [Wells et al., 1990; Hodges and Walker, 1990, 1992]. Recent kinematic models of metamorphic core complex evolution have focussed on normal-sense mylonitic shear zones and brittle low-angle normal faults which characterize these deeply exhumed terrains of mid-crustal igneous and metamorphic rocks [Wernicke, 1981] cutting the entire crust, to ductile-brittle transition zones [Miller et al., 1983] to rolling hinges related to isostatically induced footwall uplift [Wernicke and Axen, 1988; Buck, 1988; Hamilton, 1988] to coeval, fault-bounded lenses [Hamilton, 1982, 1987]. We outline a new structural model for the Tertiary exhumation of the East Humboldt-Wood Hills metamorphic terrain which relates overprinted west- and east-rooted, low-angle normal faults and shear zones to episodes of Eocene to Holocene extension.

The East Humboldt-Wood Hills metamorphic complex of northeastern Nevada lies within the hinterland of the Sevier fold and thrust belt [Snoke and Miller, 1988] (Figure 1) and is a plastically deformed igneous and metamorphic terrain which includes Archean basement rocks, probable early Proterozoic units, late Proterozoic to mid-Paleozoic metasedimentary rocks, and various Mesozoic and Tertiary igneous rocks overlain by a highly extended cover sequence of unmetamorphosed Paleozoic through Tertiary strata. These rocks are exposed in the Ruby Mountains, East Humboldt Range, Wood Hills, Pequop Mountains, and Windermere Hills (Plate 1) and record extensional processes which occurred at middle to uppermost crustal levels [Snoke et al., 1990]. Our studies in this region have focused on the variation in exposed pre-Tertiary crustal levels across the northern margin of this metamorphic complex, and the synextensional Tertiary sediments within it, in order to define the timing and magnitude of slip across major extensional fault systems.

The deepest crustal levels exposed along the northern margin of the Ruby-East Humboldt-Wood Hills metamorphic complex lie in the East Humboldt Range and Clover Hill area (Plate 1) [Snoke and Lush, 1984; Lush et al., 1988; Snoke et al., 1990; Hodges et al., 1992; Snoke, 1992], where lower Paleozoic, Proterozoic, and Archean rocks record a complex Late Jurassic through mid-Tertiary history of upper amphibolite facies dynamothermal metamorphism and igneous intrusion [Dallmeyer et al., 1986; Wright and Snoke, 1986]. These rocks lie adjacent to structurally higher metamorphosed strata exposed in the Wood Hills and Pequop Mountains to the east (Plate 1) which exhibit lower amphibolite to greenschist facies metamorphic mineral assemblages and fabrics developed during a complex Mesozoic deformational history [Thorman, 1970; Thorman and Snee, 1988; Camilleri, 1992]. Metamorphosed Paleozoic strata present in the Wood Hills are also exposed in the southern Windermere Hills [Mueller, 1990] (Plate 1) which mark the northernmost exposures of plastically deformed strata in the metamorphic complex. Paleozoic-Tertiary strata lying north and northwest in the northern Windermere Hills and southern Snake Mountains are largely unmetamorphosed (K.J. Mueller, unpublished data; Plate 1).

The abrupt transition from plastically to brittlely deformed rocks across the northern margin of the metamorphic complex occurs over a distance of 8-17 km from the northernmost East Humboldt Range to the southern Snake Mountains and may be related to lateral variation in Tertiary extensional and exhumation. An even more abrupt transition in metamorphic grade is exposed in the southern Windermere Hills where upper-greenschist grade strata are separated from essentially unmetamorphosed rocks across a north dipping normal fault. Understanding the geometry of major extensional fault systems in this region therefore depends closely on the distribution of exposed metamorphosed and nonmetamorphosed rocks.

Four major plastic-to-brittle extensional fault and shear zone systems are present which contribute to Tertiary unroofing across the northern margin of the metamorphic complex (Figure 2). These fault systems were active during separate to broadly coeval episodes of Tertiary crustal thinning and divide the region into two oppositely rooted extensional...
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Fig. 1. Index map showing the location of the study area in relationship to major tectonic elements of the northeastern Great Basin. Ranges shown include metamorphic complexes exhumed during Tertiary and late Mesozoic (?) extension.

WELLS PEAK FAULT SYSTEM

Evidence for the earliest phase of extensional faulting along the northern margin of the East Humboldt-Wood Hills metamorphic complex is present in the Wells Peak area of the southern Windermere Hills (Plate 1 and Figure 2). Mapping in this region indicates the presence of two, domiform, low-angle normal faults (Plate 2). The structurally highest fault is named the Wells Peak fault and separates plastically deformed Paleozoic strata in its footwall from unmetamorphosed Paleozoic and Mesozoic strata in its hanging wall (Mueller, in press).

Strata exposed in the footwall of the Wells Peak fault include metamorphosed equivalents of Mississippian Chainman, Diamond Peak, and Pennsylvanian Ely formations. These strata exhibit a well-developed, moderately dipping, bedding-parallel foliation and generally N-S trending lineation, defined by elongated pebbles and coarse sand grains deformed under middle greenschist facies conditions. Fabrics exposed at Wells Peak are largely nonmylonitic and do not appear related to the pervasive WNW-ESE stretching lineation and other fabrics of Tertiary age associated with the west-rooted mylonitic shear zone exposed in the northern East Humboldt Range and Clover Hill region [McGrew and Snoke, 1990; Snoke, 1992]. Metagraywackes exposed near Wells Peak contain both prolate and oblate clasts, which are not associated with asymmetric fabrics suggestive of simple shear. These fabrics are similar to metamorphic fabrics exposed in the Wood Hills and Pequop Mountains interpreted to be Mesozoic in age [Camilleri, 1992].

Conodonts recovered from metamorphosed limestone of the Guilmette Formation in the footwall of the low-angle
normal fault lying structurally beneath the Wells Peak fault yielded a Color Alteration Index (CAI) value of 6, indicating peak metamorphic temperatures of 400°-450°C before Tertiary exhumation.

An absence of exposed kinematic slip indicators along the Wells Peak fault and the uncertainty of the pre-extension geometry of footwall and hanging-wall strata preclude accurate definition of the sense-of-slip along it. Several geometric relationships suggest, however, that the Wells Peak fault is a west dipping, large displacement fault. Mapping in the southern Snake Mountains [Thorman et al., in press] suggests that the Wells Peak fault would be exposed there in rotated fault blocks, which it is not, if it were an east dipping fault. The Wells Peak fault defines an eastward opening splay with an underlying low-angle normal fault, suggesting that both may be part of a related west-rooted system. Stratigraphic units which compose the hanging wall and footwall of the Wells Peak fault remain unchanged over a distance of 17 km in the direction of slip, suggesting a shallow primary dip and large displacement. In addition, field and geophysical (e.g., gravity) data suggest that the Wells Peak fault is one splay of a clearly west-rooted fault system exposed in the southern Snake Mountains (Plate 2); these faults may all be part of a long-lived, top-to-the-west normal fault system.

Metamorphosed strata lying in the footwall of the Wells Peak fault are similar to plastically deformed Paleozoic units exposed in the Wood Hills, both in grade and style of strain [Thorman, 1962, 1970; Camilleri, 1992]. The correspondence of metamorphic rocks and the geometry of the Wells Peak fault near Moor Summit suggest that the Wood Hills region lies structurally beneath the Wells Peak fault and was partially exhumed by top-to-the-west movement along it (Plate 2). The transition from metamorphosed Mississippian-Pennsylvanian strata in the southernmost Windermere Hills to Devonian-Ordovician strata in the northernmost Wood Hills is unexposed; map relationships suggest the possibility of either an intermediate low-angle normal fault of minor displacement lying beneath the Wells Peak fault or a tightly appressed northwest verging fold, similar to those mapped by Thorman [1970] in the central Wood Hills.

Early Tertiary movement along the Wells Peak fault is substantiated by ⁴⁰Ar/³⁹Ar analyses of metamorphic muscovite from the Wood Hills [Thorman and Snee, 1988]. Their data suggest that metamorphosed Paleozoic strata exposed in the Wood Hills cooled through the muscovite closure temperatures, (about 325°-270°C, Snee et al. [1988]), at about 50 Ma. In addition, ⁴⁰Ar/³⁹Ar dating of upper amphibolite rocks from deeper structural levels in the East Humboldt Range suggests cooling through the hornblende closure temperature at about the same time [McGrew and Snee, 1991]. We interpret this as recording the cooling of footwall strata present in the southern Windermere Hills, Wood Hills, and East Humboldt Range during early Tertiary slip along the Wells Peak or other related faults.

The amount of slip along the Wells Peak fault is difficult to determine due to the poorly understood nature of vertical stacking of pre-Tertiary strata that was created during Mesozoic thrust faulting. However, this fault juxtaposes unmetamorphosed Permian limestone containing abundant undeformed fossils against middle greenshist facies Mississippian and Devonian strata. This large jump in metamorphic grade, the low regional dip of the fault, and the similarity of footwall strata over great distances in the direction of slip (about 17 km in the Windermere Hills) suggest that lateral displacement along the Wells Peak fault may be considerable and of the order of tens of kilometers.

**BLACK MOUNTAIN FAULT SYSTEM**

An east-rooted, low-angle normal fault, named the Black Mountain fault, is exposed in the Windermere Hills and Pequop Mountains (Plates 1 and 2). Strata exposed beneath the Black Mountain fault are Mississippian to Ordovician in age [Oversby, 1969, 1972] and unmetamorphosed to slightly metamorphosed, based on CAI values of 4 in Mississippian limestone [Harris et al., 1980] and incipient, crystal-plastic strain in Ordovician quartzite. Strata contained in the hanging wall of the Black Mountain fault vary from Permian to Miocene in age and are unmetamorphosed (CAI=1; Harris et al., [1980]).

On the basis of stratigraphic thickness of omitted Paleozoic units and footwall cutoff angles, displacement along the Black Mountain fault is considerable and of the order of 13-25 km. This calculation is based on the assumption of an intact section of Ordovician-Triassic strata, prior to Tertiary extension.

The Black Mountain fault exhibits a synform-antiform geometry (Plate 1) characteristic of low-angle normal faults throughout the North American Cordillera [Spencer, 1984; Buck, 1988]. This geometry has been related to flexure and isostatic uplift of the footwall during tectonic removal [Wernicke and Axen, 1988; Buck, 1988] or thinning of the hanging wall along rotating arrays of high-angle normal faults [Spencer, 1984].

Tilted, east dipping normal faults, which lie above and are linked with the underlying low-angle Black Mountain fault, are well preserved along the eastern flank of the Windermere Hills (Plates 1 and 2). Individual tilt blocks contain Tertiary strata whose age and lithofacies define extension within the hanging wall of the Black Mountain fault, and by inference, movement along it.

Late Eocene volcanic and volcaniclastic sediments (about 40.4 to 39.2 Ma; based on ⁴⁰Ar/³⁹Ar dating) are preserved along the eastern flank of the Windermere Hills and do not appear to be synextensional deposits, based on their sheet-like character across the region. Basal Tertiary strata are depositionally over lain by synextensional rocks which include about 35 Ma (based on ⁴⁰Ar/³⁹Ar dating) siltstone and older sandstone and conglomerate. Synextensional strata fill half grabens bounded by rotated, east dipping normal faults, recording thinning of the hanging wall of the Black Mountain fault and exhumation of the Windermere Hills between about 39 and 35 Ma.

**MYLONITIC SHEAR ZONE**

A plastic low-angle shear zone can be traced along strike for approximately 110 km from the western flank of the southern Ruby Mountains to the northern end of the East Humboldt Range [Snoke et al., 1990]. The rocks that define this shear zone are invariably mylonitic and range in protolith age from Archean to Oligocene.

Surface structural mapping and seismic reflection data [Effimoff and Pinezich, 1986] indicate that the shear zone chiefly dips westward and that this westward dip continues in
the subsurface. However, in the northern Ruby Mountains and at the northern end of the East Humboldt Range, detailed mapping of mylonitic foliation and lineation indicate warping and folding of the originally west dipping shear zone [see Valasek et al., 1989, their Plates 1 and 2; also A.W. Snoke, unpublished data].

In the southern Ruby Mountains the shear zone is apparently very thin (exposed thickness only 30 m, Hudec [1990] and superposed on low-grade metamorphic rocks; in the northern Ruby Mountains and East Humboldt Range the mylonitic shear zone is 1.5- to 2.0-km thick and superposed on upper amphibolite facies metamorphic rocks and various associated granitic rocks. These relations suggest greater amounts of extensional unroofing, from south to north, of rocks contained in the footwall of the mylonitic shear zone. In the southern and central Ruby Mountains, the eastern dip of footwall strata and an asymmetric cooling history indicated by K-Ar, 40Ar/39Ar, and fission-track studies suggest important rotation of an originally steep, west dipping normal fault to its present westward low-angle dip [Kistler et al., 1981; Dallmeyer et al., 1986; Reese, 1986; Hudec, 1990, 1992]. As the character of the footwall changes to the north (e.g., northern Ruby Mountains and East Humboldt Range), a primary low-angle dip for the exposed midcrustal mylonitic shear zone is suggested by its parallelism with the axial surfaces of large-scale recumbent folds [Howard, 1966; Snoke et al., 1990] and the cooling history of rocks in the shear zone [Dokka et al., 1986].

Sense-of-shear indicators consistently yield top-to-the-WNW, in plastically deformed rocks of the shear zone. In the northern Ruby Mountains, where eastward dips are common in the mylonitic shear zone, the direction of the sense-of-shear is up the plunge of the stretching lineation for this part of the extensional shear zone.

Geothermobarometry of pelitic schists from near the base of the mylonitic shear zone in the East Humboldt Range yielded a temperature and pressure estimate of 580-620°C and 3.1-3.7 kbar for mylonitic petrogenesis [Harlow et al., 1991]. The pressure estimate suggests a depth of 13-14 km for the mylonitization, although such an estimate only represents one stage of a complex thermal-kinematic evolution which may have included both higher and lower temperature and pressure conditions for the mylonitic deformation. Numerous intrusions of Mid-Tertiary granitic rocks (40±3 to 29±0.5 Ma) were deformed in the shear zone suggesting a late Oligocene or younger displacement history [Wright and Snoke, 1986; also J.E. Wright and A.W. Snoke, unpublished data]. Fission track studies, however, indicate that the mylonitic shear zone cooled through the apatite closure temperature at about 23 Ma in the northern Ruby Mountains and East Humboldt Range [Dokka et al., 1986]. These data indicate that the plastic deformation associated with mylonitization had occurred by the early Miocene, at least for the presently exposed mylonitic rocks.

The mylonitic shear zone has evolved and been overprinted by younger, brittle normal faults. These faults have both

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Fig. 3. Road-cut exposure of a low-angle normal fault exposed on the west flank of Clover Hill separating steeply dipping conglomerate of the Humboldt Formation from a footwall of brecciated, strongly foliated calcite marble. A red gouge zone forms a distinct layer along the fault surface.
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Fig. 4. Progressive down-plunge projections of east-west cross sections across the northern margin of the East Humboldt-Wood Hills metamorphic complex. (Top) Initial capture and exhumation of deep-seated rocks of the metamorphic complex along the Wells Peak fault is outlined at 50 Ma. Note that synextensional basins were not developed in the study area at this time. (Middle) Both extinct and active extensional fault systems present during rapid uplift of intermediate- to high-grade rocks in the partitioned the shear zone into various fault-bounded slices (e.g., the Horse Creek assemblage of Snoke et al. [1990]) as well as juxtaposed allochthonous, unmetamorphosed rocks onto subjacent mylonitic rocks. These brittle normal faults commonly have a low dip, although some unquestionably have been initiated at a much steeper orientation.

A spectacular example of the latter situation is where steeply, northeast tilted Miocene Humboldt Formation overlies platy Ordovician-Cambrian calcite marble along the western flank of Clover Hill (Plates 1 and 2 and Figure 3). This rotated, brittle low-angle normal fault is apparently an older element of the Mary’s River fault system that overprinted and facilitated final uplift of the mylonitic shear zone during the interval early to mid-Miocene. We envision early Miocene uplift was accomplished by the "capture" of the Oligocene mylonitic shear zone by the younger Mary’s River fault system (Figure 4) with subsequent upward displacement of the older shear zone in the footwall of the largely brittle, detachment fault system (see Davis and Lister [1988], their Figure 3 or Reynolds and Lister [1990], their Figure 3c for geometric analogs of mylonitic shear zones overprinted by brittle detachment faults).

Late deformation of the mylonitic shear zone is indicated by warping and folding of the mylonitic foliation. We infer that this deformation happened during and after the capture of the Oligocene shear zone by the younger Mary’s River fault system. Isostatically induced deformation of the footwall of the younger fault system [Spencer, 1984] apparently caused the warping and folding of the originally west-dipping mylonitic shear zone.

The mylonitic shear zone exposed in the northern East Humboldt Range appears to plunge northward beneath unmetamorphosed Paleozoic and Mesozoic strata exposed in the southern Snake Mountains (Figure 5). This variation in exposed crustal level suggests that greater amounts of exhumation, perhaps related to hanging-wall removal has occurred over the East Humboldt Range, prior to the development of the youngest segments of the Mary’s River fault system.

MARY’S RIVER FAULT SYSTEM

The west-rooted mylonitic shear zone which forms a curviplanar carapace above the high-grade metamorphic rocks of the East Humboldt Range is itself overprinted by a younger, west-rooted low-angle normal fault system. This system of low-angle normal faults, here named the Mary’s River fault system, is best exposed along the eastern margin of the Mary’s River Valley, in the southern Snake Mountains [Thorman et al., in press] and in the northeastern East Humboldt Range [Snoke and Lush, 1984; Snoke, 1992].

The Mary’s River fault system separates Tertiary strata of the Mary’s River basin in its hanging wall from unmetamorphosed and upper amphibolite-facies metasedimentary and associated granitic rocks in its footwall (Plate 1). Ranges uplifted in the footwall of this extensional
fault system include the Snake Mountains, East Humboldt Range, and Ruby Mountains. Variation in the metamorphic grade of rocks lying in these regions is largely related to the geometry and degree of exhumation along the preexisting plastic-to-brittle mylonitic shear zone, active during about 29 to 23 Ma.

On the basis of seismic reflection data [Robison, 1983; Effimoff and Pinezich, 1986], the Mary’s River basin along the latitude of the study area (Plate 1) is a deep half graben underlain by a west dipping, low-to-high-angle listric normal fault which terminates updip as high-angle fault segments and scarps along the western Snake Mountains and northern East Humboldt Range. Older segments of the Mary’s River fault system are exposed in the southern Snake Mountains [Thorman et al., in press] (Plates 1 and 2) and Clover Hill area [Snoke, 1992] (Plates 1 and 2 and Figure 4) as domed rotated normal faults which diverge eastward and bound thin sheets of tilted Tertiary-Paleozoic strata. These sheets formed initially as slices of nearly flat-lying Tertiary sediments bounded by steeply dipping normal faults above an underlying low-angle normal fault. The initial breakway in the Mary’s River fault system is defined by the easternmost occurrence of east tilted Tertiary strata, located between the Windermere Hills and Wood Hills near Moor Summit (Plates 1 and 2).

Segments of the Mary’s River fault system exposed in the southern Snake Mountains separate Tertiary-Paleozoic strata in their hanging walls from unmetamorphosed footwall strata (Plate 2) [Thorman et al., in press]. These faults diverge eastward, forming a series of fault splays which are arched over the crest of the range defining a south plunging fold (Plates 1 and 2).

Additional elements of the Mary’s River fault system are present in the northeastermmost East Humboldt Range. A major low-angle normal fault exposed here has been named for exposures near Trout Creek which define a northwest striking fault zone along the northeastern flank of the East Humboldt Range (Plates 1 and 2). The Trout Creek fault system consists of anastomosing brittle faults that partition Paleozoic strata into thin, fault-bounded slices that attenuate stratigraphic section but retain proper stratigraphic order. Older strata contained in the fault zone include Cambrian through Devonian units metamorphosed to lower amphibolite to greenschist facies, whereas younger Pennsylvanian to Permian rocks are virtually unmetamorphosed. The structurally deepest footwall of the Trout Creek fault system consists of upper amphibolite facies rocks of the northern East Humboldt Range which include Precambrian ortho- and paragneiss as well as various metamorphosed Paleozoic units intruded by abundant granitic rocks [Lush et al., 1988].

Detailed kinematic and timing relationships for the Trout Creek fault zone are incompletely understood. The fault zone is in the footwall of and is truncated by the present, Holocene (?) range-bounding fault system (Plate 1). Furthermore, the Trout Creek fault system is broadly folded at the northern end of the East Humboldt Range in the footwall of the Mary’s River fault system. It is also cut by a north to northwest striking, high-angle normal fault that separates the Tertiary rocks of the northeastern East Humboldt Range from the older rocks that occur in the Trout Creek fault system (Plate 1). This normal fault appears to be a member of the range front system on the east facing flank of the East Humboldt Range and is probably middle Miocene or younger. The northwest striking fault is itself truncated by the northeast striking Holocene range-bounding faults of the Mary’s River fault system.

Mylonitic Ordovician-Cambrian carbonate rocks occur in a fault-bounded slice of the Trout Creek fault system, suggesting a post-Oligocene bristle fault history. The Trout Creek fault system is most likely an early phase of the Mary’s River fault system or possibly a remnant of the Wells Peak system that has been subsequently overprinted by more recent fault segments. In this light the Trout Creek fault system is probably west rooted and active during the late Oligocene or early Miocene.

A probable equivalent or extension of the Trout Creek fault system is also exposed on the west flank of Clover Hill where slices of Cambrian to late Devonian metamorphosed to unmetamorphosed carbonate rocks occur above flaggy, mylonitic Cambrian-Upper Precambrian quartzite and schist [Snoke, 1992] (Plates 1 and 2 and Figure 5). This low-angle fault complex is clearly truncated by a younger, low-angle normal fault that juxtaposed steeply dipping Miocene Humboldt Formation adjacent to platy Ordovician-Cambrian calcite marble (Figure 3). These relationships also suggest that the earlier low-angle fault complex (i.e., Trout Creek fault) could be an early manifestation of the Mary’s River fault system subsequently overprinted by a younger element of that system.

We interpret the initial geometry of the Mary’s River fault system as a west dipping, low-angle normal fault with a more steeply dipping updip segment. The primary low-angle geometry of structurally deep parts of the Mary’s River fault system is well documented by seismic reflection profiles [Robison, 1983]. It is unlikely that this part of this fault has been significantly rotated, based on its great lateral extent. The kinematic evolution of the Mary’s River fault system includes (1) low-angle fault separation, leading to hanging-wall basin development and eastward tilting of Tertiary sediments by flexure of the hanging wall; (2) simultaneous, isostatic uplift of the footwall into the space created during slip along the curved, or segmented portion of the low-angle normal fault; and (3) rotation and excision of originally steeply dipping fault slices of Mary’s River basin strata as the underlying high-angle fault segment was rotated toward horizontal.

An important geometric aspect of the Mary’s River fault system includes an embayment of Tertiary strata, named the Moor embayment (Plate 1), which is defined by gravity data [Erwin, 1980] and exposures of east dipping Tertiary strata between the Snake Mountains and northern East Humboldt Range. Mapped relationships from these areas suggest that the Moor embayment was developed as elongate N-S striking fault blocks were excised from a deep subbasin in the adjacent Mary’s River basin. Tertiary strata which compose the embayment are thus slabs of synextensional strata cut out from the deep part of the Mary’s River Basin and tilted to their presently east dipping attitude. The Moor embayment is therefore unrelated to a primary, shovel-shaped fault geometry such as Sacramento Pass, northern Snake Range [e.g., Grier, 1983], but rather to the variation in thickness of Tertiary strata along the N-S axis of the Mary’s River basin.

The Mary’s River fault system offsets the Wells Peak fault along the western margin of the southern Windermere Hills, suggesting that it developed during a younger period of extension (Plate 2 and Figure 3). In addition, Wood Hills-type metamorphic clasts, although present, are very
Plate 1. Simplified geologic map of study area. Units defined are based on metamorphic grade and relationship to Tertiary extensional fault systems and shear zones. Note the locations of (1) mylonitic shear zone and underlying migmatitic metamorphic complex (East Humboldt Range and Clover Hill), (2) Wells Peak fault and Mesozoic metamorphic complex (southern Windermere Hills and Wood Hills), (3) Mary's River fault system and associated synextensional Tertiary sediments (Snake Mountains, East Humboldt Range, and Wood Hills), (4) north dipping normal fault (southern Windermere Hills), and (5) Black Mountain fault and associated synextensional Tertiary sediments (northern Windermere Hills). This map was compiled from our own studies in the Windermere Hills and East Humboldt Range, in addition to studies in the Snake Mountains, East Humboldt Range, and Wood Hills by other workers. Please refer to the reference map insert for more detailed information from specific ranges.
Plate 2. Simplified cross sections located across major Tertiary extensional fault systems. Note overprinting of mylonitic shear zone by the Mary’s River fault system on A-A’, B-B’ and C-C’. Also note exposures of the Wells Peak fault and subjacent metamorphic rocks on B-B’ and the oppositely rooted Black Mountain fault with subjacent unmetamorphosed rocks on A-A’. D-D’ defines the north dipping normal fault which bounds the northern margin of plastically deformed rocks in the metamorphic complex. Offset equivalents of the Wells Peak fault are visible on the north side of D-D’ which are not exposed in the northern Windermere Hills. C-C’ contains the most highly exhumed structural levels exposed in the metamorphic complex. Note the complex cross cutting of low-angle normal faults along the west side of Clover Hill and the westward thinning wedge of metamorphic rocks bounded by the mylonitic shear zone and Mary’s River fault system. Units marked on cross sections include Quaternary sediments (Qs), Plio-Pleistocene Hay Ranch Formation (Thr), Miocene Humboldt Formation (Th), Eocene volcanic strata (Tv), Triassic Thaynes Formation (Ttr), Permian Murdock Mountain and Pequop formations (Pm and Pp), undivided Permian strata (Pu), Carboniferous Ely and Diamond Peak formations (Cdp), Mississippian Chiefman Formation, Melandco Sandstone, and Tripton Pass Formation (Mc, Mm and Mtp), Devonian Guiltmette Formation, shale (western facies), and Sevy and Simonson dolomites (Dg, Dsh, and Ds), Silurian Roberts Mountain Formation (Srm), undivided Ordovician strata (Ou), Ordovician-Cambrian marble (OCm).
uncommon in the Tertiary stratigraphic section in the northeastern East Humboldt Range until about 15 Ma [Snoke et al., 1990]. Therefore, metamorphic strata now exposed in the Wood Hills were not completely exhumed by slip along the Eocene (?) Wells Peak fault but rather were deeply eroded only after subsequent uplift occurred by slip along the cross-cutting, west-rooted Mary's River fault system.

The timing of slip along the Mary's River fault system is also defined by exposed tilt blocks of Tertiary sediments in the southern Snake Mountains, northern East Humboldt Range, and in the intact half graben of the Mary's River basin itself. Seismic reflection profiles, acquired perpendicular to the basin margin, define east dipping Tertiary strata which thicken toward the faulted eastern margin of the Mary's River basin [Robison 1983; Effimoff and Pinezich, 1986, Plate 2]. These strata, which include Miocene Humboldt and Plio-Pleistocene Hay Ranch formations, range in age from early Middle Miocene to Quaternary time (about 15-16 Ma or older to Recent) suggesting that half graben development and hence low-angle normal faulting have been active throughout this time interval. In addition, early to mid-Miocene sediments (about 16 to 23 (?) Ma, or older) exposed in the northern East Humboldt Range and southwestern flank of the Snake Mountains consist of coarse-grained sheet flood and megabrecchia deposits, suggesting the presence of an active range front during this time. The thick alluvial fan sequence present in these areas is not present at the same stratigraphic interval in the adjacent fault block to the east, exposed along the eastern Snake Mountains (marked as Tv + Th on east flank of Snake Mountains in Plate 2, A-A' [Thorman et al., in press]). This suggests that the west dipping low-angle normal fault which separates these two fault blocks was active during deposition of these coarse-grained sediments. This fault is presently exposed in the central and eastern flanks of the southern Snake Mountains where it separates Permian Murdock Mountain Formation in its hanging wall from Mississippian Melandco sandstone and Devonian shale in its footwall [Thorman et al., in press, Plate 2]. Ongoing evolution of the Mary's River fault system has rotated this Miocene normal fault to its present shallow, east dipping orientation.

The recency of slip along the Mary's River Fault system is defined by steeply tilted late Miocene sediments (about 8-9 Ma, based on fission-track zircon ages) exposed in the northeastern East Humboldt Range. In addition, the present range-bounding fault is defined by Quaternary fault scarps which may be the updip termination of the major low-angle normal fault flooring the Mary's River half graben, suggesting that low-angle segments of the Mary's River fault system are presently active.
HIGH-ANGLE, NORTH AND EAST DIPPING NORMAL FAULTS

Extension is also expressed in the metamorphic complex by north and east dipping high-angle normal faults in the Windermere Hills and northern East Humboldt Range. One of the earliest faults of this type includes a north dipping, high-angle normal fault exposed across the southern Windermere Hills and northern Pequop Mountains. This fault separates a half graben filled with south dipping conglomerate and sandstone in its hanging wall from unmetamorphosed Permian footwall strata in the northern Pequop Mountains. Permian footwall strata are depositionally overlain by younger Tertiary strata (about 10-12 Ma, based on fission track dating), suggesting that older Eocene strata were uplifted and eroded during movement along the north dipping normal fault. Synextensional strata exposed in the half graben suggest a minimum of 1 km of displacement during a short (7), poorly constrained interval between about 12-35 Ma.

The north dipping normal fault can be traced along strike for 21 km to the west where it displaces metamorphosed footwall strata of the Wells Peak fault about 3 km from unmetamorphosed footwall strata of the Black Mountain fault to the north (Plate 2, D-D'). The north dipping high-angle normal fault therefore postdates and crosscuts the Wells Peak and Black Mountain fault systems and is the boundary between metamorphosed and unmetamorphosed strata, east-west striking normal faults have also been described from other parts of the eastern Great Basin [Bartley and Taylor, 1992], where they were originally interpreted as strike-slip faults [Ekren et al., 1976].

The youngest normal faults exposed in the metamorphic complex include east dipping, high-angle normal faults in the Windermere Hills and northern East Humboldt Range. These faults offset all the previously discussed extensional fault systems and shear zones in the metamorphic complex, suggesting that they are Miocene or younger in age. East dipping, high-angle normal faults preserved in the Windermere Hills and along the western margin of Toano Basin bound half grabens which contain as much as 3 km of synextensional strata. These include two half grabens preserved in the Windermere Hills filled with strata inferred to date 10 to 12 Ma. In addition, a half graben in Toano Basin which lies adjacent to the Windermere Hills may contain sediments as young as Pliocene or Pleistocene.

DISCUSSION

Exhumation of middle to upper crustal rocks within the East Humboldt-Wood Hills metamorphic complex is related to the development of five major extensional fault systems active from mid-Eocene and possibly older to Holocene (Figures 2, 4, and 5). The complex history of middle to upper crustal thinning in this region is manifested by temporally distinct to broadly coeval, low- to high-angle normal faults and shear zones which successively overprint one another. Earliest exhumation of the metamorphic complex may have occurred in the mid-Eocene along the west-rooted Wells Peak fault, itself overprinted by the oppositely rooted, structurally overlying, late Eocene, Black Mountain fault system (Figures 2, 4, and 5). Subsequent extension in the late Oligocene to middle Miocene was accommodated by the west-rooted mylonitic shear zone and the cross cutting, Mary's River fault system (Figures 2, 4, and 5). The youngest faults preserved in the metamorphic complex compose an array of deeply penetrating high-angle normal faults which crosscut preexisting extensional fault systems (Figures 2, 4, and 5).

The record of early extension in the metamorphic complex is associated with deep-seated, low-angle normal-sense shear zones which do not preserve extensional basins in their hanging walls in the study area. Later extension, along much higher level low- to high-angle normal faults produced the late Eocene to Holocene (7) basins present in the region today. The structural style of the individual low-angle normal faults associated with exhumation of the metamorphic complex appears similar to many other extended regions in the Basin and Range province [e.g., Spencer, 1984; Howard and John, 1987; Wernicke and Axen, 1988; Buck, 1988]. However, on a larger scale the Tertiary structural evolution of the East Humboldt-Wood Hills metamorphic complex is largely read to overprinting of separate normal fault systems, commonly associated with a change in the sense of displacement.

A significantly different aspect of the East Humboldt-Wood Hills metamorphic complex from other apparently similar, regions is that much of the exhumation of high-grade rocks and the mylonitic shear zone which overlies them was facilitated by movement along later, overprinted fault systems. The original updp termination of the mylonitic shear zone, if it did extend into the brittle upper crust, should be present outside the study area, in ranges lying to the east.

An important aspect of Neogene and Quaternary extension in this region is the coincidence of range fronts with high-angle normal faults. These faults appear to crosscut older systems of low-angle normal faults, and although part of a long-lived history of extension, they may represent a fundamental change in structural style, at least at the crustal level presently exposed in the metamorphic complex.

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