Abstract:
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Conclusions differ from those of previous workers in that the quartzite gravel is older than the limestone conglomerate, both units are Late Cretaceous rather than Paleogene, and basal exposures of Renova mudstones produce a Duchesnean rather than a Chadronian local fauna. The broader Conclusions support disruption of a broad Paleogene depositional basin by the present geometry of basins and ranges in southwestern Montana. Extensional faulting did not predate 30 Ma and has offset the Renova Formation by 3,350-5,300 m (11,000-17,400 ft) relative to adjacent grabens. The dense welding of the Huckleberry Ridge Tuff on the range crest suggests that the 1,100 m. (3,600 ft.) of relief relative to outcrops in the adjacent Madison valley is largely the result of tectonism during the Quaternary.

SYN- AND POST-LARAMIDE GEOLOGY OF THE SOUTH-CENTRAL GRAVELLY RANGE, SOUTHWESTERN MONTANA

by

Ernest Jan Luikart

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Earth Sciences

MONTANA STATE UNIVERSITY - BOZEMAN
Bozeman, Montana

April 1997

APPROVAL

of a thesis submitted by

Ernest Jan Luikart

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ACKNOWLEDGMENTS

I would like to thank my graduate advisor Dr. Dave Lageson for his support, advice and encouragement, and for turning me toward the light of structural geology. Thanks to committee members Drs. Jim Schmitt and Tony Barnosky for their helpful discussions and advice. Special thanks to committee member Dr. Mike O'Neill of the U.S.G.S. for initial inspiration, training in geologic mapping, and feedback through all the phases of this project. I profited from discussions with Dr. Bill Locke and my undergraduate advisor at Wesleyan University, Dr. Jim Gutmann.

Dr. Malcolm McKenna of the American Museum of Natural History introduced me many years ago to the joys of field vertebrate paleontology in the northern Rockies. More recently, he curated the fossils from this study, had key specimens prepared, and allowed me to wander unguarded in the Frick collection.

I cannot find words to thank Wendy Herrick for her help, faith and support, and for waiting patiently for our honeymoon during the course of this thesis.

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ABSTRACT

The geologic history of post-Laramide basin evolution in the foreland of southwestern Montana has been a matter of controversy. A complex assemblage of Upper Cretaceous to Tertiary sedimentary and volcanic rocks which record some of that history are exposed on and near the crest of the Gravelly Range. Past interpretations of their relations and tectonic implications conflict. The present investigation of a portion of the southern Gravelly Range crest helps to resolve the physical stratigraphy and ages of the post-Laramide deposits and suggests the following sequence of events: (1) syn- and post-Laramide erosional beveling of the Madison-Gravelly arch; (2) Late Cretaceous deposition of quartzite gravel from a thrust belt source, locally containing Archean metamorphic clasts from a foreland source; (3) conformable transition to deposition of limestone conglomerate derived from the Blacktail-Snowcrest arch, with interbedded siltstone, sandstone and lacustrine limestone, deposited prior to the end of Laramide deformation; (4) final movement of Laramide faults; (5) erosion represented by a 28-38 my-long unconformity; (6) deposition of tuffaceous mudstones beginning in the Duchesnean (40-37 Ma) and proceeding into the Whitneyan (32-29 Ma) interrupted by erosion at about 32 Ma; (7) eruption of basalt flows from local vents between 33 and 30 Ma; (8) minor erosion followed by early Miocene (23 Ma) eruption of an isolated mafic volcanic center; (9) emplacement of Huckleberry Ridge Tuff at 2.1 Ma after erosion or nondeposition of Miocene strata; (10) significant uplift of the range in Quaternary time; (11) Pleistocene deposition of glacial moraines in the deeper valleys, and ongoing mass-movement and colluvial processes.

Conclusions differ from those of previous workers in that the quartzite gravel is older than the limestone conglomerate, both units are Late Cretaceous rather than Paleogene, and basal exposures of Renova mudstones produce a Duchesnean rather than a Chadronian local fauna. The broader conclusions support disruption of a broad Paleogene depositional basin by the present geometry of basins and ranges in southwestern Montana. Extensional faulting did not predate 30 Ma and has offset the Renova Formation by 3,350-5,300 m (11,000-17,400 ft) relative to adjacent grabens. The dense welding of the Huckleberry Ridge Tuff on the range crest suggests that the 1,100 m. (3,600 ft.) of relief relative to outcrops in the adjacent Madison valley is largely the result of tectonism during the Quaternary.

INTRODUCTION

Efforts to unravel the post-Laramide sedimentary and tectonic history of southwestern Montana have resulted in a number of possible scenarios for regional Cenozoic basin evolution (Reynolds, 1979; Fields et al., 1985; Fritz and Sears, 1993; Ruppel, 1993). Southwestern Montana has been shaped by a complex tectonic history from Late Cretaceous through Cenozoic time. Major episodes of deformation include spatially and temporally overlapping thin-skinned (Sevier) and thick-skinned (Laramide) contractional deformation in the Late Cretaceous to early Tertiary, followed by at least one phase of extension in the mid-Tertiary, and late Tertiary through Quaternary tectonic influence of the passage of the Yellowstone hot spot (Anders and Sleep, 1992; Pierce and Morgan, 1992; Fritz and Sears, 1993). Although most models of regional geologic events share these basic elements, there is ongoing debate about the number, timing, and style of basin-forming episodes during the Cenozoic.

Numerous studies have focused on the stratigraphic record of Tertiary basin-fill in intermontane basins of southwestern Montana as the key to unraveling post-Laramide geologic history. Similarities among basins include homotaxial lithostratigraphic sequences and vertebrate faunal successions, with closely matching radiometric age limits where volcanic rocks are available. This suggests that the individual basins share a common history to a large degree (Fields et al., 1985). It was recognized that this observed "basin unity" (Monroe, 1976) required mechanisms, such as climate, which operate on a regional scale (Kuenzi and Fields, 1971; Monroe, 1976; Thompson et al., 1982). Other proposed tectonic models and geologic histories propose that the semi-isolated extensional basins which preserve Tertiary basin-fill are not the basins in which those strata were deposited. The "basin unity," at least for the lower part of the Tertiary system, may reflect deposition as a broad, relatively continuous sheet which was subsequently partitioned during one or more extensional episodes (Thompson et al., 1981; Fritz and Sears, 1993; Thomas, 1995). Remnants of the Tertiary system which exist outside of the present extensional fault-bounded basins preserve important clues about the complexity of basin evolution in southwestern Montana.

Purpose of Study

A heterogeneous assemblage of syn- and post-Laramide coarse- and fine-grained sedimentary rocks and volcanic flows overlie an erosional surface between about 2,740 and 3,050 m (9,000-10,000 ft) on the crest of the Gravelly Range in southwestern Montana. Previous conclusions about the tectonic and depositional significance of these rocks vary significantly, because the field relations and ages of the scattered outcrops were interpreted in conflicting ways (Scott, 1938; Atwood and Atwood, 2945; Mann, 1954; 1960; Hadley 1969b; 1980; Gutmann et al., 1989; Ruppel, 1993).

The primary goal of this study is to resolve the chronology of Late Cretaceous through Tertiary geologic events in the southern Gravelly Range based on an in-depth, mapping-based investigation of high-elevation syn- and post-Laramide strata, and to discuss the tectonic implications of that chronology, in the light of proposed tectonic models. On a local scale, the chronology is relevant to the uplift history of the range relative to adjacent grabens. On a regional scale, it can help test hypotheses of Cenozoic geologic evolution in southwestern Montana. Additionally, newly reported fossil mammal faunas which contribute age control at several localities are recognized as a significant Duchesnean local fauna.

Geologic Setting

The Gravelly Range lies in the Rocky Mountain foreland of southwestern Montana (Fig. 1). This region is bounded on the north by the "southwest Montana transverse fault zone", a 120-km-long east-trending fault zone which forms the southern margin of the Helena salient of the Sevier thrust belt (Schmidt and O'Neill, 1983). To the west, the southwest Montana reentrant of the Sevier thrust belt is characterized by structural overlap and interference of Sevier- and Laramide-style deformation (e.g. 'Dillon cutoff' of O'Neill et al., 1990). The foreland is bounded on the southwest and south by frontal thrust sheets and the Snake River Plain. To the east, the foreland grades into the northern Great Plains.

The present physiography of the region surrounding the Gravelly Range is characterized by broad intermontane basins separated by high mountain blocks (Fig. 2). The underlying extensional structure represents a northernmost extension of the Basin and Range structural province, flanking the northern margin of the Snake River Plain (Reynolds, 1979, but see Ruppel, 1993). The Gravelly Range also lies within a region of tectonic disruption caused by thermal effects of the passage of the Yellowstone hot spot (Anders and Sleep, 1992; Pierce and Morgan, 1992; Fritz and Sears, 1993).

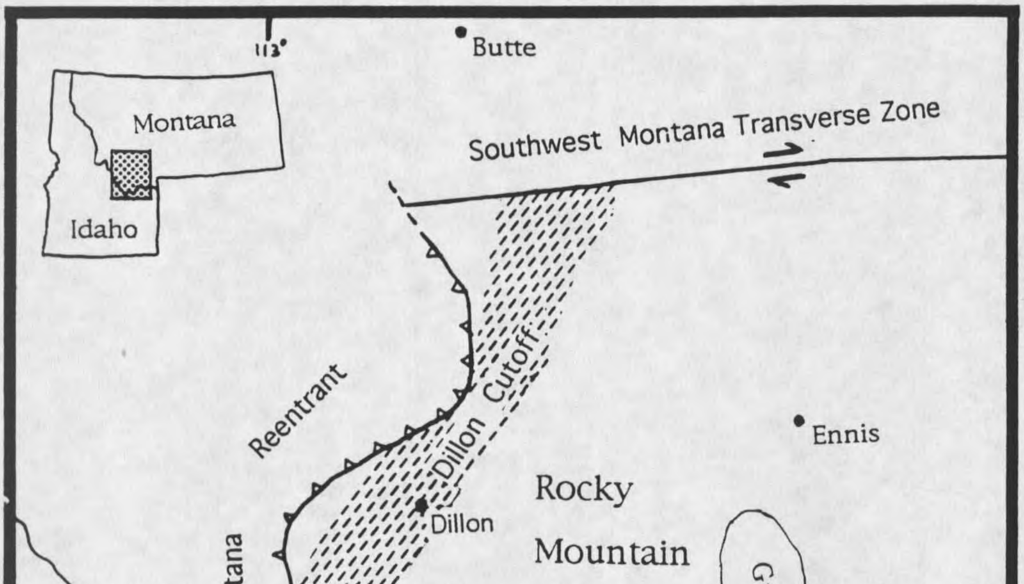

Figure 1. Simplified tectonic map of southwestern Montana showing the Rocky Mountain foreland bounded by the margins of the Sevier thrust belt and the Snake River Plain. Location of Gravelly Range is outlined; other ranges not shown.

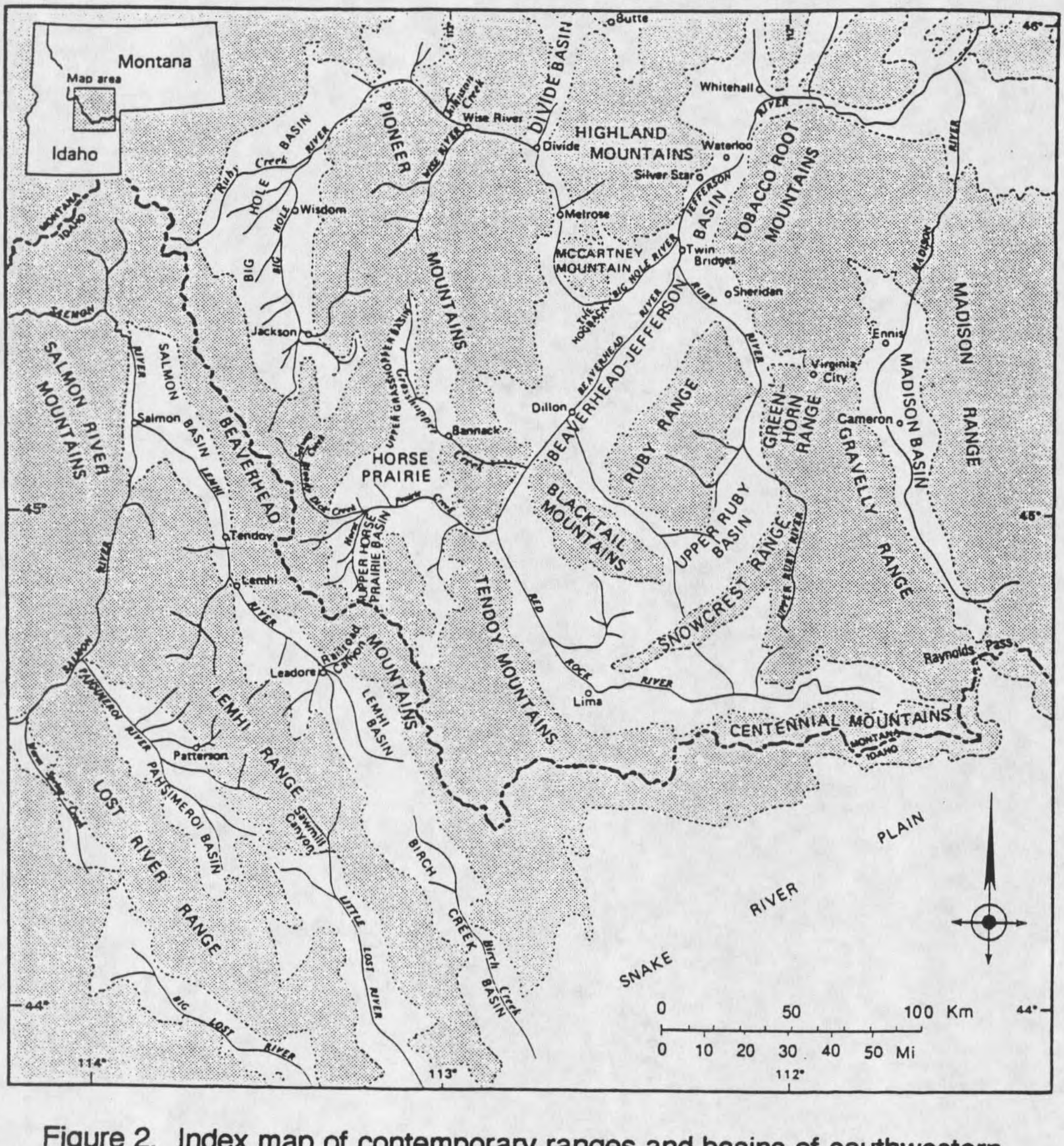

Figure 2. Index map of contemporary ranges and basins of southwestern Montana and east-central Idaho (from Ruppel, 1993).

Methods

Field work by previous authors (Mann, 1954, 1960; Hadley, 1960, 1969b, 1980; Gutmann et al., 1989) and reconnaissance by J.M. O'Neill and the author was used to choose a field area on the crest of the Gravelly Range for detailed geologic mapping. This area consists of most of the U.S.G.S. 7.5" Bighorn Mountain topographic quadrangle, spanning T.10S and T.11S, R.2W, in the Beaverhead National Forest, Madison County, Montana (Fig. 3). The field area was selected for its outcrops of post-Laramide sedimentary and volcanic rocks, in particular for localities that might show the field relations of different lithosomes, or that might yield vertebrate fossils.

Mapping of Paleozoic through Tertiary rock units and geologic structures was done directly onto the 7.5" Bighorn Mountain topographic map, with strike and dip measurements, lithologic descriptions, and fossil locality data kept in a separate field notebook. Completion of mapping for a few areas on the eastern side of the map was done using USDA color stereo aerial photographs housed at the U.S. Forest Service Beaverhead District headquarters in Ennis, Montana. Nomenclature for Mississippian to Lower Cretaceous strata shown on the map and cross-section A-A' follows that of Mann (1954, 1960), Hadley (1960, 1969a, 1969b, 1980) and Tysdal et al. (1989).

One sample of unweathered basalt for $^{40}Ar/^{39}Ar$ dating and XRF analysis was collected from a basalt flow overlying Tertiary sedimentary rocks, thus providing age control and testing the correlation of flows in the field area to those previously dated elsewhere in the Gravelly Range. The radiometric analysis was performed by the New Mexico Geochronological Research Laboratory (Appendix); the XRF analysis was performed by the Washington

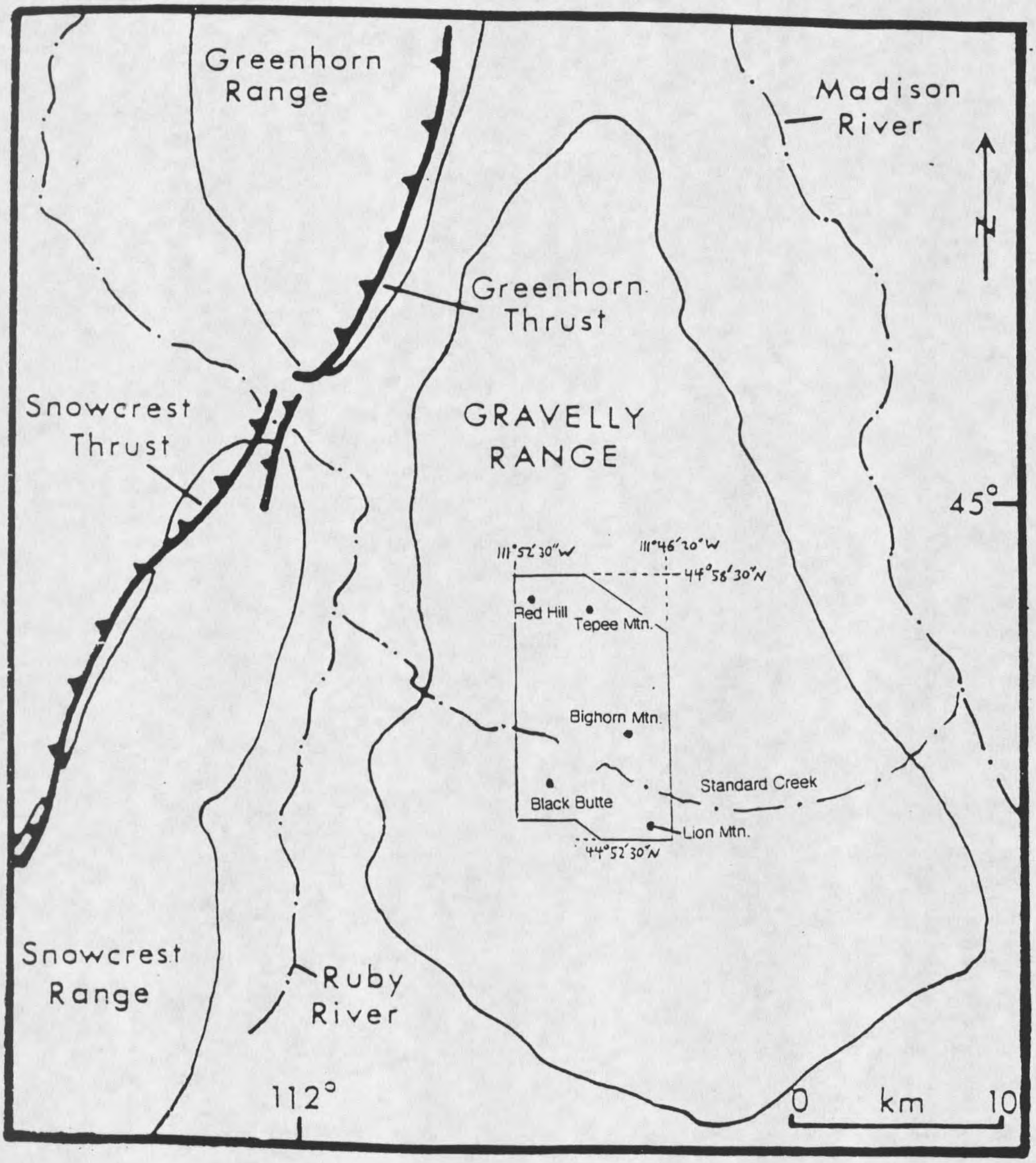

Figure 3. Index map of Gravelly Range, showing map area and selected features (modified from Gutmann et al., 1989).

State University GeoAnalytical Laboratory (Appendix).

Mammalian fossils were collected from four localities, three of which had been identified prior to this project. Specimens were prepared at the American Museum of Natural History in New York, using standard micropreparatory techniques. All specimens from this study are permanently curated at the AMNH, in accordance with the U.S. Forest Service paleontological permit stipulations.

The paleontologic data from this study and from previous vertebrate collections made in the field area by the Museum of Comparative Zoology at Harvard in the 1950's, and by the American Museum of Natural History in the 1980's, were combined into taxonomic lists for the four localities. The biochronologically significant taxa from these lists were used to establish the probable North American Land Mammal Age of each locality. Assignment of numerical time intervals and epochs to the relevant North American Land Mammal Ages follows the calibration of Prothero and Swisher (1992).

The lithologies, mutual stratigraphic relations and time-significant information compiled from several sets of exposures within the map area were combined to generate a generalized stratigraphic column with associated time scale. This stratigraphic column was compared with the generalized results of basin studies in southwestern Montana (Fields et al., 1985), in order to clarify issues of Cenozoic basin evolution.

Tertiary Basin-Fill Nomenclature

The earliest attempts to describe and interpret the significance of Tertiary basin-fill sequences preserved in fault-bounded basins of southwestern

Montana led to the misleading term "Bozeman lake beds" (Peale, 1896), based on an overestimation of the role of lacustrine systems during deposition. The nomenclature was revised by Robinson (1963), who defined the Bozeman Group as: "...the Tertiary fluvial, aeolian and lacustrine rocks which accumulated in the basins of western Montana after the Laramide orogeny..." The present widely accepted scheme of Bozeman Group lithostratigraphy recognizes two unconformable, lithologically distinct depositional sequences (Fig. 4). The Renova Formation (Kuenzi and Fields, 1971), of late Eocene to early Miocene age, is predominantly fine-grained and rests on an unconformity cut into pre-Tertiary rocks, or locally on volcanics and interbedded volcaniclastic rocks associated with the middle Eocene Challis and Lowland Creek volcanic fields. The Renova is overlain with angular unconformity by the predominantly coarse-grained Sixmile Creek Formation (Robinson, 1967) of late Miocene to Pliocene age.

Hanneman and Wideman (1991) argued against the use of Bozeman Group terminology, citing the presence of fine- and coarse-grained rocks in both formations "to the extent that it is in many cases impossible to recognize either one." They used a sequence stratigraphic (allostratigraphic) approach based on calcic paleosol zones tied to seismic reflection data to recognize five depositional sequences in southwestern Montana valleys. Both the conventional and allostratigraphic schemes are constrained by radiometric dates and mammalian biostratigraphy, and can be correlated with the numerical time scale, the North American Land Mammal Ages, and the epochs (Fig. 4). It should be noted that some features of regional importance are recognized by both systems, particularly the late Eocene and early to middle Miocene angular unconformities.

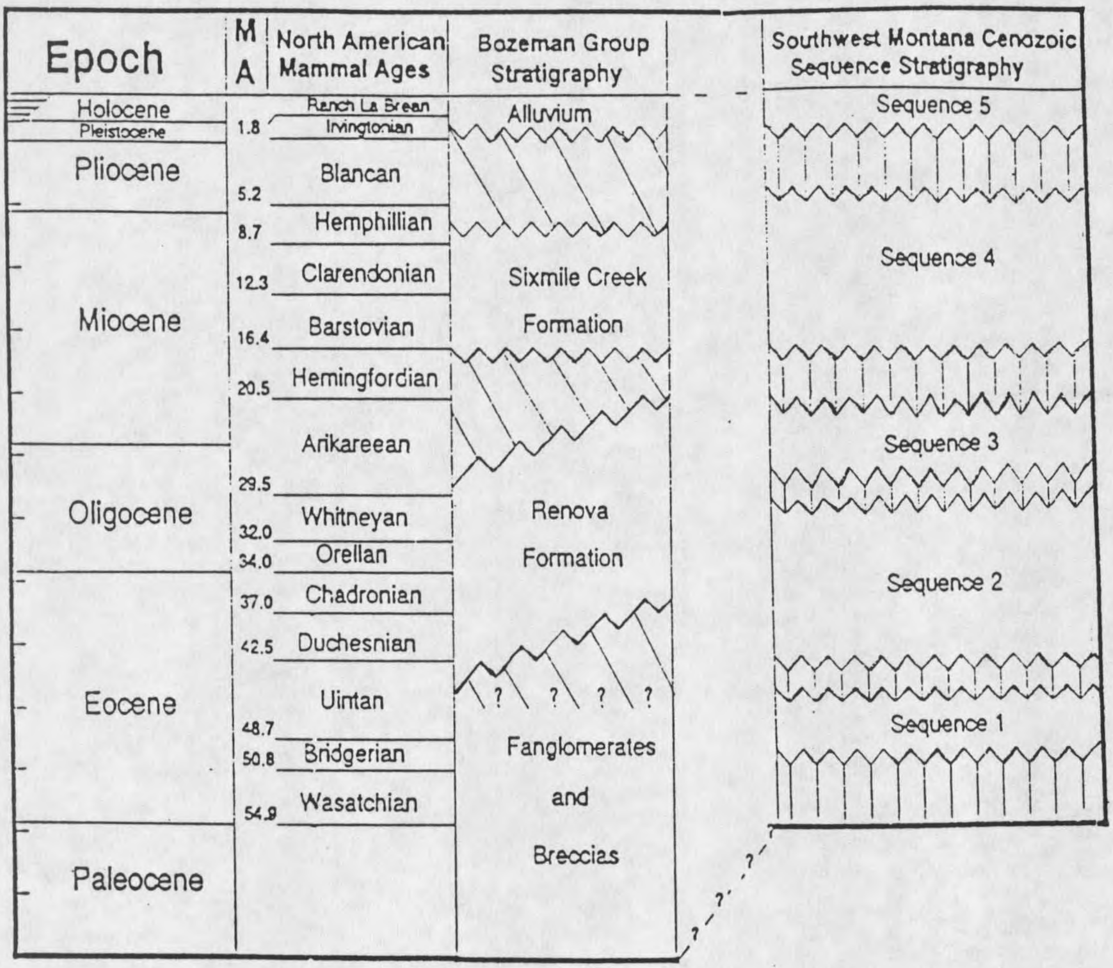

Figure 4. Comparison of Tertiary stratigraphic schemes for southwestern Montana basins: conventional Bozeman Group lithostratigraphy shown on the left and the allostratigraphy of Hanneman and Wideman (1991) shown on the right. Sequence 1 is primarily volcanic rocks associated with the Challis and Lowland Creek volcanic fields; the other sequences are predominantly sedimentary (modified from Hanneman and Wideman, 1991).

This report retains the name 'Renova Formation' in reference to the dominantly fine-grained, felsic tuffaceous sedimentary rocks which overlie a regional unconformity in the field area and contain Eocene to Oligocene mammal faunas. These rocks constitute a mappable unit within the field area, and match the criteria for extension of the term 'Renova Formation' from its type area in the Jefferson basin (Kuenzi and Fields, 1985). No equivalents of the Sixmile Creek Formation (Robinson, 1967) were found in the map area.

Tectonic Models

Conflicting theories concerning the post-Laramide tectonic history of southwestern Montana can be categorized according to the number and style of distinct basin-forming episodes proposed for the Cenozoic. Some workers have argued that the existing extensional fault-bounded basins have been active since the Eocene, with the late Eocene through Oligocene Renova Formation and equivalent strata deposited in the structural basins which now preserve them (Chadwick, 1981; Fields et al., 1985; Ruppel, 1993). Fields et al. (1985) stated that, "Delineation of the intermontane basins took place during early and middle Eocene time as a response to regional intra-arc extension." Pardee (1950) also proposed that the Tertiary "Lake beds" accumulated in areas corresponding approximately to the present basins, although his model included erosion of the ranges plus basin aggradation (= "peneplanation") to create a surface of low relief during the Tertiary, followed by re-elevation of ranges during a late Cenozoic (Pliocene) stage of block uplift.

Based on a general geologic investigation of the Gravelly Range, Mann (1954, 1960) proposed Oligocene burial of post-Laramide low-relief topography by volcaniclastic material, hinting at a regionally broad Paleogene depositional setting. The idea of disruption of older basin geometries has been incorporated in more recent tectonic models. Thompson et al. (1981) argued that the regionally developed Hemingfordian angular unconformity between the Renova and Sixmile Creek formations marks the disruption of a widespread Renova blanket and the beginning of differentiation into the modern basins and ranges. Such a broad "Renova basin" may have developed partly as a flexural basin extending from an uplifted rift shoulder in extreme western Montana (Janecke, 1994; 1995; Vandenburg et al., 1996). Alternatively, the massive early to middle Eocene Challis and Absaroka volcanic fields might have provided the western and southeastern basin margins, and possibly generated slight subsidence of the intervening area through isostatic adjustment, sufficient for aggradation of Renova sediments.

Other studies have added a younger phase of uplift and extension, linked to the arrival of the Yellowstone hot spot during the last 6 Ma (Anders and Sleep, 1992; Fritz and Sears, 1993; Thomas, 1995; Thomas et al., 1995; Sears, 1995). In these recent models, much of the existing extensional topography of southwestern Montana is latest Miocene or younger and may not be strongly reflective of Basin and Range extension (Thomas, 1995).

Information from this study can help rule out some of the geologic histories and tectonic models mentioned above.

PALEOZOIC-MESOZOIC GEOLOGY AND LARAMIDE STRUCTURES

Pre-Laramide stratigraphy

Only Mississipian and younger strata crop out in the field area (geologic map, Plate 1). The Paleozoic section in the Gravelly Range is more than 440 m thinner than in the Snowcrest and Greenhorn ranges immediately to the west. The thinning occurs abruptly across the Snowcrest-Greenhorn thrust fault system which lies between them (Mann, 1954, 1960; Hadley, 1960). The units absent in the Gravelly Range are the Cambrian Park Shale, Pilgrim Dolomite, Snowy Range Formation, and Mississipian Big Snowy Group. Drilling data from the Centennial Valley south of the Gravelly Range demonstrate a similar abrupt thinning of the Paleozoic section southeastward from the Snowcrest Range. This may indicate recurrent activity along a zone of crustal weakness between the Snowcrest-Greenhorn and Gravelly ranges (Hadley, 1960). This zone of weakness was structurally inverted during Cretaceous contractional deformation to become the Snowcrest-Greenhorn thrust fault system (Perry et al., 1981).

In contrast, the Mesozoic section is largely similar to that in adjacent regions. An exception is a 90 m-thick section of Triassic red beds in the field area (Woodside Formation) found only in the southern Gravelly Range; the unit pinches out within a few km to the north of the field area.

The youngest pre-Laramide unit in the field area is a sandstone unit overlying shales of the Thermopolis Formation. It was included in the Thermopolis Formation by Hadley (1960; 1980), but is herein referred to as the Muddy Formation following Tysdal et al. (1989).

Laramide Structures

The entire pre-Laramide section dips generally 8-20 degrees westward throughout the field area, with local deviations near folds and faults. This is characteristic of the Gravelly range as a whole, and reflects Late Cretaceous uplift of the area as the western limb of a NNW-trending Laramide-style uplift, the Madison-Gravelly arch (Scholten, 1967) (Fig. 5). The Gravelly Range area was also the eastern limb of a huge asymmetric syncline (Ruby syncline) which developed between the Madison-Gravelly arch and the Blacktail-Snowcrest arch to the west. These structures resulted from predominantly E-W shortening across the foreland of southwestern Montana.

Timing of Laramide shortening in the southwest Montana foreland is based on palynology of synorogenic strata shed from the basement-cored uplifts, and on limited radiometric dates. The uplift of the Madison-Gravelly arch is dated in part by a Maastrichtian palynomorph assemblage in the middle part of the Sphinx Conglomerate, a synorogenic alluvial fan deposit which was derived from the Scarface thrust plate in the Madison Range (Decelles et al., 1987). The Scarface thrust is one segment of a major system of thrust faults, the Hilgard fault system, which controlled eastward translation of the Madison-Gravelly uplift (Tysdal et al., 1986). Movement on the Hilgard fault system predates intrusions which "stitch" the thrust system, radiometrically dated at 68-69 Ma, providing a Maastrichtian upper limit on uplift (Tysdal et al., 1986).

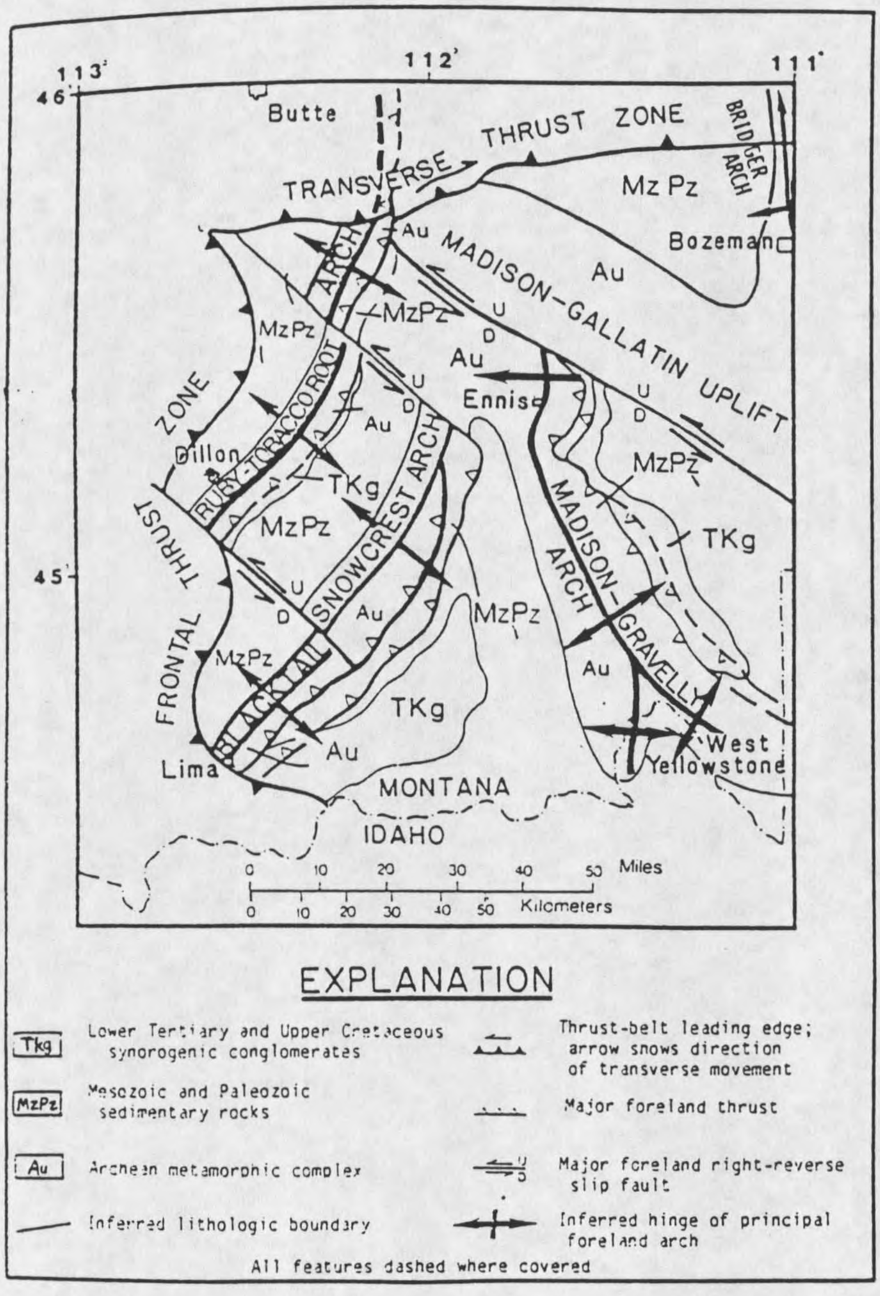

Figure 5. Schematic paleotectonic map of southwestern Montana, showing interpreted structural pattern of Laramide-style structures in the Late Cretaceous foreland (from Schmidt et al., 1988).

The Lima Conglomerate of the Antone Peak Formation (Beaverhead Group) is a synorogenic conglomerate shed from the Blacktail-Snowcrest arch (Fig. 5) (Ryder and Scholten, 1973). Based on palynomorphs from the top of the conglomerate, uplift of the Blacktail-Snowcrest arch appears to have been essentially completed by middle Campanian time (78-81 Ma) (Nichols et al., 1985). It is therefore somewhat older than final Madison-Gravelly uplift.

The relatively early contractional history of this region produced a buttressed foreland on which the Sevier thrust belt impinged. Eastward propagation of the thrust belt was impeded, accounting for the southwest Montana recess of the Sevier thrust belt (Fig. 1) (Eldredge and Van der Voo, 1988; Schmidt et al., 1988).

In the field area, thrust faults dip westward at 20-40 degrees. Translation on these faults was probably not large; the greatest observed throw is about 220 m, placing the Amsden Formation on top of Dinwoody Formation siltstones and dolomites along the Bighorn Mountain thrust (Mann, 1960) (see map, Plate 1). Slickenlines preserved on a silicified fault surface at the top of Bighorn Mountain record dip-slip motion of the hanging wall to the ESE (Fig. 6). Northward, the fault splays through Madison Group limestone in a fault zone characterized by breccia-filled karst. It is not known whether the faulting exploited a karst zone or karsting developed subsequently along the fault zone. South of Bighorn Mountain the fault dies out rapidly into an anticline (Fig. 7), and east-west contraction is transferred to another thrust which continues southward. The anticline is therefore interpreted as a fault-propagation fold, cored by a blind thrust (see cross-section A-A' of Plate 1). These and other relatively small east-vergent thrust faults characteristic of the Gravelly Range may be out-of-the-syncline thrusts generated by the space problem in the core

Figure 6. Silicified fault surface exposed in the thrust of Bighorn Mountain, showing kinematic indicators. Pencil is parallel to slickenlines indicating ESE dip-slip movement of the hanging wall. Note the set of right-lateral shear fractures.

Figure 7. Anticline inferred to be cored by a blind continuation of the Bighorn Mountain thrust, view looking SSW from Bighorn Mountain. The anticline is cored by Madison Group limestone. The upper cliff-forming unit is the Quadrant Formation overlain by Shedhorn Sandstone.

of the Ruby syncline as it became tightly folded and locally overturned to the east. Alternatively, they may be small synthetic basement-cored thrusts developed on the gentle west limb of the Madison Gravelly arch. The post-Laramide erosion surface underlying the gravel and conglomerate discussed in the next section probably began to develop synchronous with Laramide shortening.

SYN- AND POST-LARAMIDE GEOLOGY

Erosion Surface

One of the striking features in the field area is a widespread, generally low-relief angular unconformity which truncates the west-dipping Paleozoic and Mesozoic strata and all Laramide folds and faults in the map area. Much of the present low-relief topography which characterizes the range crest is an expression of this surface due to ongoing removal of the overlying, poorly lithified strata. The erosion surface has been interpreted as a remnant of subdued Late Cretaceous to middle Eocene topography which developed during and/or after Laramide contraction, but before initiation of Tertiary basin formation (Mann, 1954; 1960; Fields et al., 1985; Ruppel, 1993). At most localities within the map area, the erosion surface is best dated by 37-40 Ma mammal faunas in overlying tuffaceous mudstones (see Vertebrate Paleontology of the Renova Formation). However, the mudstones are not the oldest deposits above the unconformity. Where remnants of older gravels and conglomeratic units are present, the angular unconformity beneath them is probably Late Cretaceous and coeval with late-stage Laramide deformation (see discussion of the conglomerate of Red Hill).

In the northern part of the Gravelly Range, Hadley (1960, 1980) noted a several degree northeastward dip of the erosion surface toward the Madison valley. Within the field area, its average elevation is 2,800-2,840 m (9,200-

9,300 ft). The topography of the erosion surface is consistent with a generally horizontal orientation, with the exception that the overlying conglomerate of Red Hill is found at successively lower elevations eastward across the north end of the map area, indicating significant Late Cretaceous topography developed where the Morrison through Quadrant formations were eroded (Map, Plate 1).

The steep-sided and deeply incised drainages, such as the headwaters of Cottonwood, Standard, Horse and Ruby creeks, cut through the projected level of the erosional surface, and are more recently superimposed features; No Tertiary rocks are preserved within them or at elevations lower than 2,780 m (9,120) ft. However, other smaller drainages appear to be exhumed paleovalleys; a small steep cirque-like drainage on the south side of Bighorn Mountain, 0.5 km east of the Bighorn thrust, contains traces of white Renova ash at 3,000 m (9,800 ft) and unusually polished blocks of Shedhorn Sandstone are present in the upper part of the drainage (Fig. 8).

Sedimentary and Volcanic Rocks

The angular unconformity beveling the range top is overlain by several lithologically distinct sedimentary deposits and volcanic rocks. Two factors contribute to the uncertainty and disagreement in the literature concerning the mutual relations and age limits of some of these strata: only patchy remnants of the rocks are left on the Gravelly Range due to glaciation and ongoing erosion, and each of the facies is limited in its distribution such that there is no single outcrop belt in which all lithologies are present.

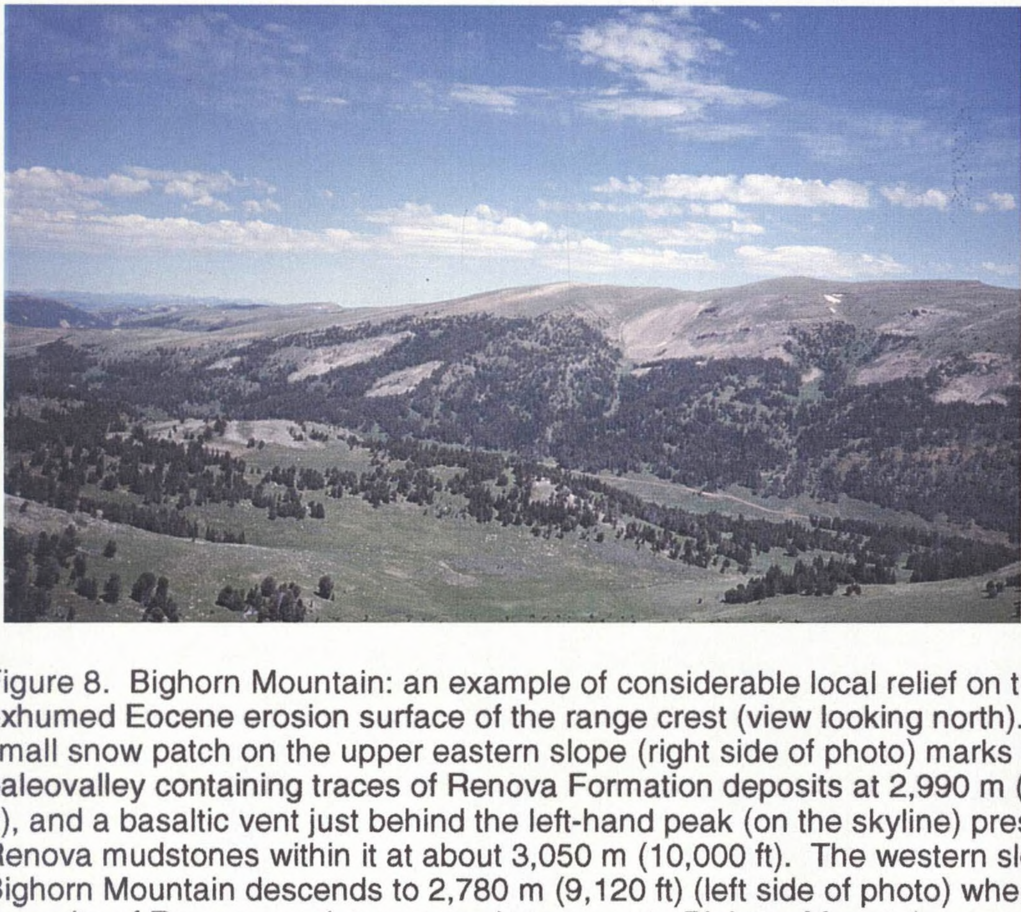

Figure 8. Bighorn Mountain: an example of considerable local relief on the exhumed Eocene erosion surface of the range crest (view looking north). The small snow patch on the upper eastern slope (right side of photo) marks a paleovalley containing traces of Renova Formation deposits at 2,990 m (9,800 ft), and a basaltic vent just behind the left-hand peak (on the skyline) preserves Renova mudstones within it at about 3,050 m (10,000 ft). The western slope of Bighorn Mountain descends to 2,780 m (9,120 ft) (left side of photo) where deposits of Renova mudstone are also present. Bighorn Mountain was therefore apparently buried in Eocene-Oligocene time.

Gravel of Black Butte

Description and Distribution . The stratigraphically lowest, and therefore oldest, post-Laramide deposit in the field area is an unlithified pebble to boulder gravel, herein informally referred to as the gravel of Black Butte after its best-known exposure at the head of a landslide immediately west of Black Butte. At that locality, the clast composition consists almost entirely of very well-rounded quartzite pebbles and cobbles in a deposit up to 10 m thick (Fig. 9). Minor amounts of Archean metamorphic and Paleozoic limestone clasts exhibit a lesser degree of rounding, and several large (3 m) angular boulders of cherty Shedhorn Sandstone are present. A few rounded clasts of mafic igneous rock were noted.

The gravel of Black Butte is everywhere characterized by a coarse angular quartz sand matrix and varies from 0-10 meters thick. It varies laterally in its clast composition from nearly all quartzite cobbles to dominantly Archean metamorphic cobbles and boulders. Remnants of a mixed clast assemblage is scattered along Monument Ridge at 2,835 m (9,300 ft) elevation. At the north end of Monument Ridge the composition varies from dominantly quartzite pebbles and cobbles cropping out around the base of Red Hill, to dominantly Archean gneiss and schist boulders near the southern side of Lazyman Hill. J. Michael O'Neill (pers. comm., 1997) reports that in outcrops south of the field area, Archean metamorphic gravel can be distinguished from, and underlies, quartzite cobble gravel . This distinction was not observed within the field area, although it cannot be ruled out since clasts of unconsolidated material are subject to downslope mixing as they are exposed.

The gravel of Black Butte pinches out rapidly eastward. Tepee Mountain (noted on the map as benchmarks 9603T and 9560AT on the western margin of

Figure 9. Gravel of Black Butte, exposed in a landslide scarp immediately west of Black Butte, showing clast lithology dominated by very well rounded Proterozoic quartzite cobbles. Geologic hammer for scale.

Tepee basin) marks its easternmost remnant, where a small outcrop of dominantly Archean boulders is exposed below late Eocene mudstones on the west face of the mountain. The gravel is not present in exposures on the east side of the mountain. South of Red Hill and Tepee Mountain, the gravel is restricted entirely to the western edge of the map area, from Monument Ridge to the west side of Black Butte.

Age Limits and Regional Correlation . The age of the gravel of Black Butte is poorly bracketed. It lies on sandstone of the Early Cretaceous Muddy Formation west of Black Butte, and both it and a conformably overlying conglomeratic unit are overlain by late Eocene rocks. Furthermore, the gravel exposure west of Black Butte has a long history of conflicting age and depositional interpretation in the literature. The crushed cobbles within the deposit (see discussion in Gutmann et al., 1989) and striations trending nearly down-dip (westward) in the sandstone underlying this deposit (Fig. 10), contributed to early interpretations as an Eocene glacial till (Scott, 1938; Atwood and Atwood, 1945), and to Mann's (1954, 1960) hypothesis of mudflow emplacement during middle Eocene to early Oligocene time.

Gutmann et al. (1989) correlate the gravel with the informally named "Divide quartzite conglomerate" of the Upper Cretaceous Beaverhead Group. The Beaverhead Group is an assemblage of foreland- and thrust belt-derived syntectonic deposits in southwestern Montana which contain several poorly correlated quartzite conglomerate units (Schmitt et al., 1995). The closest outcrop belt of Beaverhead Group quartzite conglomerate lies in the Monida Pass area about 60 km to the southwest of the field area. Paleocurrent trends in the Monida Pass area are northeast to north (Ryder and Scholten, 1973), so it is

Figure 10. Crushed quartzite cobbles from the gravel of Black Butte, shown on the striated dipslope of Muddy Formation sandstone which underlies the gravel at this locality (immediately west of Black Butte). Pencil for scale.

conceivable that distal parts of this deposit could have onlapped the western limb of the Madison-Gravelly arch. Proterozoic quartzites which crop out in the Pioneer Mountains 90 kilometers west of the Gravelly Range have also been suggested as a possible source area for the gravel of Black Butte (Ruppel, 1993). The subrounded cobbles and boulders of Archean gneiss were probably derived from a foreland uplifts, probably the Blacktail-Snowcrest arch, given its early unroofing history.

Alternatively, the gravel of Black Butte could conceivably have been recycled sometime after the Late Cretaceous from quartzite-rich units of the Beaverhead Group. Both Mann (1960) and Ruppel (1993) interpreted it as being only slightly older than the overlying late Eocene succession (thought at that time to be early Oligocene mudstones). However, arguments for the age of the locally overlying conglomerate of Red Hill presented in the next section indicate that the gravel of Black Butte is most likely Campanian or Maastrichtian.

Conglomerate of Red Hill

Description and Distribution. In the northern half of the map area, the gravel of Black Butte is overlain, apparently conformably, by a complex succession of interbedded red siltstone, sandstone and lacustrine limestone, with lenticular bodies of limestone conglomerate. Because the limestone conglomerate is the most widely distributed of these facies and often occurs without the other facies as isolated lenticular bodies, both in the map area and elsewhere in the range, this succession is informally referred to as the conglomerate of Red Hill.

In the Red Hill/Lazyman Hill area, basal siltstones and limestones of this sequence contain lenses of quartzite gravel in an angular quartz sand matrix, essentially identical to the underlying gravel of Black Butte except that the average clast size is smaller, ranging from pebbles to small cobbles. The lacustrine limestone facies consists of a sparry matrix, locally containing fossil snails, stromatolites and oncolites. Discontinuous stringers of coarse sandstone and intraformational siltstone and limestone rip-up clasts are also common within the limestone facies. The most numerous type of freshwater snail from the limestone facies is a Lymnaeid, probably *Stagnicola* ; similar Lymnaeids are known from Jurassic to Pleistocene lacustrine rocks. A less common snail was referred to *Biomphalaria*, which has been noted in pre-Chadronian rocks in the Cenozoic basins of Wyoming (Emmett Evanoff, pers. comm., 1996). The presence of this snails is consistent with a pre-late Eocene age limit, but add no further age refinement.

The large lenticular conglomerate bodies contain rounded to subangular Cambrian to Pennsylvanian limestone pebbles, cobbles and locally boulders, in a red sandy siltstone matrix (Fig. 11). Minor amounts of Archean schist and gneiss clasts and sandstone cobbles are present as well. The conglomerate appears to be mostly clast-supported but is locally matrix supported. It tends to be unstratified to crudely stratified.

To the south along Monument Ridge and eastward at Tepee basin, outcrops of the limestone conglomerate facies are found by themselves in what appear to be remnants of paleochannels cut into Mesozoic and Paleozoic strata. The conglomerate is exposed at lower elevations from west to east across the northern part of the map area.

Limestone conglomerate of the same description is found along the range crest in the Varney quadrangle to the north (Hadley, 1969b, 1980), and other exposures are found well south of the map area. However, no part of the

Figure 11. Outcrop of the conglomerate of Red Hill, showing conglomerate composed dominantly of Paleozoic limestone clasts and minor Archean clasts, overlain by lacustrine limestone at the north side of Red Hill. Geologic hammer for scale.

conglomerate of Red Hill is found in the sections at Black Butte, Lion Mountain and other localities in the southern part of the map area, indicating either nondeposition or erosion there prior to deposition of late Eocene mudstones.

At the south end of Lazyman Hill, the uppermost lithosome in a dominantly siltstone-lacustrine limestone sequence is a thin bed of coarse litharenite composed of very angular quartz grains and biotite-bearing metamorphic fragments. Of significance for age interpretation, the beds at this locality appear to be gently folded where they onlap a thrust wedge of Shedhorn Sandstone which pinches out rapidly southward beneath them (Plate 1, northwest corner of map). The aspect of the bedding elsewhere is approximately flat-lying.

On the west face of Tepee mountain, an enigmatic outcrop of angular blocks and breccia composed of cherty Shedhorn Sandstone in a red silty matrix was mapped as part of the conglomerate of Red Hill. It seems likely that the deposit is of sedimentary origin, and the angular clasts were eroded from immediately adjacent topographic highs in the Shedhorn Sandstone to the northeast and southeast. Alternatively, the breccia may be of fault-cataclastic origin, in which case the fault responsible for the brecciation is not obvious. The breccia is not traceable laterally, and typical limestone conglomerates of the conglomerate of Red Hill are exposed on the east side of Tepee Mountain with no sign of the breccia.

Age Limits and Regional Correlation . The broad age limits for the conglomerate of Red Hill are similar to that for the gravel of Black Butte: it could be as old as Late Cretaceous syntectonic conglomerates (Beaverhead Group) in the region, and it cannot be younger than the overlying late Eocene

(Duchesnian) mudstones. However, a number of observations considered below strongly suggest that it is Late Cretaceous.

Hadley (1969b, 1980) assigned the limestone cobble conglomerate in the northern Gravelly Range to the Sphinx Conglomerate in the Madison Range. Decelles et al. (1987) also referred to the sequence at Red Hill as a distal equivalent of the upper Sphinx, deposited on the western, lower-gradient flank of the Madison-Gravelly arch. The Sphinx Conglomerate was deposited between about 75 and 58 Ma (DeCelles et al., 1987). If the correlation is correct, the conglomerate of Red Hill would likely be of late Maastrichtian or Paleocene age (Decelles, et al., 1987).

There are several difficulties with previous correlations of the limestone conglomerate of the Gravelly Range with the Sphinx Conglomerate, however. Neither the presence of an oxidized matrix, nor an abundance of Paleozoic carbonate clasts are particularly exclusive features on which to base a correlation. Oxidized matrix could have been derived locally from redbeds of the Woodside Formation during fluvial transport, or could have developed during intense weathering in a warm, humid Late Cretaceous or Paleocene climate (Berggren and Prothero, 1992), or could even be of diagenetic origin. Potential source areas for Cambrian to Pennsylvanian limestones would have existed in all of the Laramide foreland uplifts, as well as in the thrust belt to the west and south.

A description of clast composition in the Sphinx Conglomerate *sensu stricto* did not note any Archean clasts, and Cambrian Flathead Sandstone clasts appear only in the uppermost part of the Sphinx section (Graham et al., 1986). In their provenance model for the Sphinx, Graham et al. (1986) noted only "Precambrian possibly exposed" at the top of their sequence. Slight deformation of the conglomerate of Red Hill on the margin of a thrust fault suggests that deposition of the conglomerate of Red Hill predated the end of Laramide deformation. If the Madison-Gravelly arch was ever sufficiently unroofed to provide Archean lithologies, it was almost certainly not early enough to predate Laramide deformation in the field area.

In contrast, the Lima Conglomerate was derived from the Blacktail-Snowcrest arch during Santonian through middle Campanian time (Ryder and Scholten, 1973; Nichols et al., 1985), significantly before Sphinx deposition. The Lima Conglomerate contains Archean clasts in its upper part (Schmitt, 1995).

Additionally, the outcrops of limestone conglomerate step-down more than 60 meters in elevation from west-to-east across the northern part of the map area. In the absence of intervening Cenozoic normal faults, this suggests transport from an uplifted source area to the west. The alternative, that of complete infilling of the erosional topography between Monument Ridge and Tepee basin, followed by erosional removal of all but a few remnants, seems less likely.

Based on the above evidence, the most likely correlative for this unit is the Lima Conglomerate, in which case the conglomerate of Red Hill was deposited at about 78 Ma (Nichols et al., 1985), toward the end of Laramide tectonism west of the Gravelly Range.

The lack of intertonguing relations of the conglomerate of Red Hill with overlying late Eocene (Duchesnean) tuffaceous mudstones suggests that the top of the succession is marked by an unconformity. Both the structural evidence for the late-stage synorogenic deposition of the conglomerate of Red

Hill, and its correlation with either the Sphinx or Lima conglomerate, indicate that this unconformity represents a gap of 28-38 million years.

Renova Formation

Description and Distribution. Scattered outcrops of poorly indurated, light-colored, tuffaceous mudstones assigned to the Renova Formation comprise the most widely distributed post-Laramide, pre-Quaternary sedimentary deposit in the field area and across the Gravelly Range as a whole. The widely scattered outcrops of this tuffaceous mudstone are usually capped by Oligocene basalt flows, and sometimes intruded by small vents of scoriaceous agglomerate. The sedimentary outcrops are often fossiliferous, yielding mammal taxa on which its late Eocene to middle Oligocene age limits are partly based. Carbonate concretions are locally abundant in the mudstones, and sometimes produce well-preserved fossils, although they do not appear to nucleate specifically around fossil bone.

Most of the deposits in the western and northern portions of the field area overlie one or both of the more coarse-grained sequences previously described. Elsewhere, the mudstones and basalt flows directly overlie the west-dipping Paleozoic-Mesozoic section with angular unconformity.

By far the thickest section of Paleogene sedimentary rocks in the Gravelly Range is exposed on the west side of Lion Mountain. The sedimentary section is preserved here because Lion Mountain is a major Oligocene volcanic center; the infrastructure of dikes and small sills extending outward from the central vent, as well as the basalt flows at the summit, have protected the poorly consolidated sedimentary strata from erosion. About 240 m of sedimentary section rests on the Madison Group and is capped by basalt flows (Fig. 12). The lower part of the section here is typical of the other outcrops of Paleogene fine-grained, felsic, poorly-bedded mudstone, but the upper 80 meters, which is significantly younger than any Renova deposits elsewhere in the field area, contains some thin layers and small trough cross-stratified lenticular bodies of granule to pebble conglomerate within sandy siltstone and mudstone. This is one of the few places where the structural attitude of beds in the Renova can be discerned. They are very close to flat-lying, with eastward dips of a few degrees in some areas (Gutmann et al., 1989). The clasts in the conglomeratic layers are mostly granules and pebbles of Paleozoic limestone with basaltic scoria and lapilli. The basaltic clasts may have accumulated during early local eruptions at about 31 Ma (Gutmann et al., 1989).

Around the margin of the Black Butte volcanic neck, basal Renova mudstone and small lenses of tuffaceous limestone have also been protected from total erosion by younger volcanic rocks, in this case the resistant Black Butte plug and the basaltic talus fields surrounding it (Fig. 13). At Tepee Mountain, a 30 m-thick fossiliferous mudstone section is intruded by a basaltic vent and capped by a basalt flow. Scattered localities show only a few meters to a few centimeters of mudstone beneath basalt flow remnants, and are sometimes unmappably small at the 1:24,000 scale. Thin outcrops of mudstone are capped by basalt flows at the southern end of Monument ridge, and a very small deposit which is not protected by basalt is found on top of the conglomerate of Red Hill at the southern end of Lazyman Hill. Evidence for the thickness of the original Renova mudstone blanket, in addition to the Lion Mountain section, includes the traces of mudstone on and near Bighorn Mountain (Fig. 8), where an original mudstone thickness of 250 m is indicated,

Figure 12. View of the west side of Lion Mountain, showing the thick section of soft Renova sedimentary rocks overlying the Madison Group and capped by basalt flows. Note the large north-trending diabase dike cutting the section at upper left.

Figure 13. View of the Black Butte volcanic neck, looking northwest. The base of the butte is surrounded by basaltic rubble capping massive light-colored mudstones of the Renova Formation.

closely comparable to the total thickness of about 240 m preserved at Lion Mountain.

Age Limits and Regional Correlation . The tuffaceous rocks fit the description of the Renova Formation as proposed by Kuenzi and Fields (1971) in the Jefferson basin, both in terms of their stratigraphic position above a widespread unconformity and primarily fine-grained felsic lithology. Mammal faunas and radiometric dates support this correlation.

Kuenzi and Fields (1971) noted that the composition of the lower part of the Renova Formation (Climbing Arrow Member) in the Jefferson basin was approximately 81 percent volcanic glass- and pumice-bearing montmorillonite mudstone. The Climbing Arrow Member, as it was extended to the upper Ruby basin 25 kilometers west of the Gravelly Range, was described as mostly sandy montmorillonite mudstone (Monroe, 1976). In the Gravelly range, the mudstone at Black Butte is dominated by shards of volcanic glass, with interstitial carbonate and 5-10 percent silt-size fragments of plagioclase and biotite (Gutmann et al., 1989). In the northern part of the Gravelly Range, Hadley (1980) reported that correlative tuffaceous Paleogene sediments consisted of 70-98 percent glassy shards and 2-25 percent mineral fragments. A sample from Black Butte was composed of 68 percent silica; this high silica content is probably representative of much of the Renova Formation, and indicates a rhyolitic to dacitic source (Gutmann et al., 1989).

Deposition of the Renova began at 40-37 Ma, based on mammalian biochronology and recent time scale calibration (Prothero and Swisher, 1992), and continued at least until 30.8 $\pm$ 0.7 Ma based on a radiometric date from the top of Lion Mountain (Gutmann et al., 1989). If deposition continued beyond this time, the younger rocks have been eroded.

The Renova Formation in the field area appears to have a disconformity within it, representing 3-4 Ma of the early Chadronian to late Orellan or early Whitneyan, based on evidence at Lion Mountain and Tepee Mountain. At Lion Mountain, a Chadronian titanothere jaw was recovered low in the section, below a 31.4 ± .7 Ma (Whitneyan) airfall ash and overlying Whitneyan taxa. Despite extensive prospecting, no paleontological evidence for an Orellan sequence has been found there, although there is a significant section which has not produced many fossils. At Tepee mountain, Duchesnean (40-37 Ma) taxa are found in mudstones directly overlain by a basalt flow dated at 32.38 ± 0.64 Ma (see Appendix), which calibrates to the late Orellan/early Whitneyan (Prothero and Swisher, 1992). This indicates a gap of 4 to 5 Ma, accounting for the entire Chadronian and most or all of the Orellan interval. The most likely explanation is that both the Tepee Mountain and Lion Mountain sections contain a disconformity which is overlain by early Whitneyan or late Orellan rocks, and which varies laterally in its removal of underlying strata. The section exposed at Black Butte is thick enough that the disconformity could be present there, but further collecting with associated stratigraphic information is needed to determine this.

The Renova Formation in the Gravelly Range fits into a regional scenario of widespread aggradation of fine-grained, ash-rich sediments deposited in a setting dominated by low-energy floodplain, pond and stream channel environments throughout southwestern Montana (Kuenzi and Fields, 1971; Fields et al., 1985). Atypical features of the depositional sequence in the Gravelly Range include the probable erosional disconformity removing much of the Chadronian-Orellan interval and the 33-30 Ma alkali basalt flows and scattered eruptive centers. These volcanics are distributed throughout the Gravelly Range, and correlate with a much thicker sequence of flows in the Virginia City area approximately 40 kilometers to the north. The flows there range in age from about 34 to 30 Ma and total almost 550 meters in thickness. All of these basaltic rocks have been assigned to the middle Dillon Volcanics Member of the Renova Formation, interpreted as mantle wedge melts extruded on the eastern margin of the Paleogene Renova basin prior to Basin and Range extension (McDowell and Fritz, 1995; McDowell et al., 1997, in press). However, the basalt flows and intrusions of the Gravelly Range are mapped as a unit distinct from the sedimentary Renova Formation rocks in this report (Plate 1).

The Renova Formation of southwestern Montana may have been physically continuous with the White River Formation (or Group) of Wyoming and the northern Great Plains during much or all of the Oligocene, although this may never be possible to test conclusively. The lithologic and faunal similarities between the exposures near Black Butte and outcrops of White River Formation rocks just south of Yellowstone Park, northwestern Wyoming, were noted by Love et al. (1976). Traces of White River Formation in many areas of Wyoming suggest that it had a wide distribution there prior to erosional removal (Emry et al., 1987).

<u>Basalt and Phonolite of Black Butte</u>

<u>Description and Distribution</u> . Black Butte, the highest peak in the Gravelly Range, is located in the southwest corner of the map area (Figure 13). It is interpreted as an early Miocene volcanic neck composed primarily of alkali

basalt and diabase (Spaid-Reitz, 1980), with pods and dikes of the potassic nepheline-bearing rock tephritic phonolite intruding the diabase near the summit (Gutmann et al., 1989).

Black Butte intruded a section of beveled, west-dipping Lower Cretaceous through Permian strata overlain by the gravel of Black Butte and basal Renova mudstones (see cross-section A-A', Plate 1). The only eruptive product attributed to this volcanic feature are remnants of mineralogically distinctive thin tan tuff lying on Renova mudstones near the butte. These may have slumped downhill since emplacement due to massive downslope movements of the mudstones (Gutmann et al. 1989).

A number of hydrothermal deposits of massive gypsum with chert nodules are found in the Morrison Formation at the south end of Monument Ridge, 3 to 4 km north of Black Butte. These formed along a northeast-trending fault zone, possibly as a result of hydrothermal circulation driven by heating of the country rock as Black Butte was emplaced (Munger, 1995). The deposits form a number of funnel-shaped karst holes near the Gravelly Range road, but occur as a linear trend of large protruding blocks exposed at the head of a landslide on the southern terminus of Monument Ridge. The karst morphology is due to the dissolution of gypsum by near-surface water. Expression of some of the deposits as blocks, rather than sinkholes, probably reflects the recency of the landslide which exposed them. No other rock types related to the eruption of the Black Butte volcanic center are found in the area.

Age Limits and Regional Correlation . The Black Butte volcanic neck is dated by a whole-rock K-Ar analysis at about 22.9 ± 1.2 Ma (early Miocene) by Marvin et al. (1974). Assuming this date is correct, Black Butte is anomalous in that no other volcanic centers of similar age are documented in the region. The northern Rocky Mountain region as a whole was experiencing relative volcanic quiescence during this time (Chadwick, 1981). It is possible that this date may not be accurate. Given the advances in isotope dating over the past 20 years, redating of Black Butte should be done, but it was beyond the limits of this thesis project.

Huckleberry Ridge Tuff

Description and Distribution . Welded ash-flow tuff, 1 to 2 m thick, was found in one small outcrop capping a 2,926 m (9,600 ft) peak which forms the southern boundary of Tepee basin in the northeastern part of the field area. The base of the unit is a densely welded, dark grey vitrophyre containing sanidine phenocrysts up to 3 mm long. It becomes lighter in color and more porous, but still firmly welded, toward the top with the upper third a light pinkish-grey color, phenocryst-poor, and containing numerous flattened pumice fragments. The characteristics of this deposit match the criteria for emplacement as a high-temperature pyroclastic flow (Fisher and Schmincke, 1994)

The glassy welded base of the ash-flow tuff lies partly on Oligocene basalt, and partly on an unidentified 3 m thick, dark grey to brown, welded ash-flow tuff which contains abundant sanidine phenocrysts. This enigmatic unit underlying the zoned welded tuff described above is massive, lacks any obvious cooling zonation or bedding and is densely welded. It cannot be traced laterally for any distance. It has been suggested that this unit is a remnant of the tuff of Kilgore (Lisa Morgan, pers. comm., 1996), which was erupted from the Heise volcanic field of the eastern Snake River Plain 70 km to the south at 4.3

Ma (Pierce and Morgan, 1992). Alternatively, it could be a lower flow unit within the same composite sheet as the zoned upper unit. A 2 m-thick unconsolidated white ash underlies these welded tuffs; although it does not show stratification, it may represent a ground surge deposit (Fisher and Schmincke, 1994) associated with the emplacement of the ignimbrite sheet.

Age Limits and Regional Correlation. The 1 to 2 m thick welded zoned rhyolitic ash-flow tuff described above is most likely the Huckleberry Ridge Tuff, erupted from the Yellowstone Plateau volcanic field at 2.1 Ma (Obradovich and Izett, 1991). In the absence of a radiometric date, this identification is based on: (1) proximity to the eruptive center; (2) physical characteristics including color, grain size and phenocryst content of the cooling zones (L. Morgan, pers. comm., 1996); (3) widespread distribution of the Huckleberry Ridge Tuff, including outcrops in other ranges surrounding the Yellowstone Plateau (Izett and Wilcox, 1982; Pierce and Morgan, 1992). Other outcrops of similar welded ash-flow tuff assigned to the Huckleberry Ridge Tuff are found at high elevations south of the field area (Mann, 1960; O'Neill et al, 1995) and in the Varney quadrangle in the northern Gravelly Range, although the highest outcrop there lies below 2,135 meters (7,000 feet) (Hadley, 1969a; 1969b; 1980).

Samples from the basal, middle and upper cooling zones of the tuff were examined by L. Morgan of the U.S. Geological Survey. Their high degree of welding favors Quaternary faulting, rather than surge of the ignimbrite up a major topographic slope, as the dominant mechanism to account for the tuff's present high elevation (1,100 m) above correlatives in the adjacent Madison Valley (L. Morgan, pers. comm., 1996). This is because a high particle-density pyroclastic flow capable of dense welding would tend to follow ground contours and remain at lower elevations, whereas a pyroclastic surge sufficiently expanded to surmount high barriers would not be hot enough to weld densely upon emplacement.

Quaternary Deposits

Deposits younger than the Huckleberry Ridge Tuff include a few scattered boulders of uncertain origin, small amounts of glacial till, and widespread landslide deposits, in addition to talus fields and colluvium locally reworked into alluvium by small mountain streams. The Quaternary deposits discussed here are omitted from the stratigraphic sections and the generalized stratigraphic column shown in later chapters, because they do not contribute significant Cenozoic tectonic information.

Glacial Till

Small hillocks of poorly sorted, poorly exposed, unconsolidated material in the lower parts of Standard, Cottonwood, Ruby and Horse creeks are probably remnants of Pleistocene lateral and ground moraines. Suspected small glacial deposits were mapped together with the younger Quaternary colluvial and alluvial deposits in which they are found, because differentiating them was not deemed relevant to this report. The glacial component of Quaternary deposits is more evident at elevations lower than those in the map area; the Standard Creek drainage, for example, contains several large lateral moraines a few km east of the map area and about 550 m lower than the crest of the range.

Boulders of Uncertain Origin

A few scattered large metamorphic boulders, usually of granitic gneiss, were observed in the field area and adjacent parts of the range top. They were initially interpreted to be large relicts from eroded deposits of the gravel of Black Butte, which is locally dominated by Archean metamorphic boulders. However, one such boulder was found on top of the coarse litharenite capping the conglomerate of Red Hill on the southern side of Lazyman Hill, at 2,871 m (9,420 ft) elevation. Other isolated boulders, 2 to 3 m in diameter, rest on Paleozoic and Mesozoic rocks at somewhat lower elevations north of the Bighorn Mountain quadrangle. If these few allochthonous boulders are not part of the gravel of Black Butte, how and when they were brought to the high surface of the range is unclear, and hypotheses regarding them may be difficult to test. Pleistocene glacial origin can be ruled out, because Archean lithologies are only exposed in the Gravelly Range at elevations much lower than that of the field area.

Landslide deposits

Evidence of mass movement at various scales in the Gravelly range is almost ubiquitous (O'Neill et al., 1995). Deposits mapped as landslides usually lie downslope from arcuate scarp surfaces, and are characterized by hummocky topography and numerous ponded depressions. Most of the landslides moving toward the Ruby River on the western side of the field area are on dip slopes of relatively resistant Muddy Formation sandstone and the basal sandstone of the Kootenai Formation.

Landslides extending eastward from the Red Hill area of Monument Ridge are composed of a jumbled mixture of all the lithologies found in the gravel of Black Butte and the conglomerate of Red Hill. Most other landslides involve the more fine-grained, poorly indurated facies abundant in the Mesozoic and Tertiary systems, and some of these deposits may be more accurately classified as earthflows, probably subject to ongoing intermittent movement at various rates dictated by groundwater saturation. The clay-rich rocks most often involved in mass movements include the Morrison Formation, the Kootenai Formation above the basal sandstone member, the Thermopolis Shale, the Renova Formation, and to a lesser degree the Dinwoody and Woodside formations.

Landslide movement in the Gravelly Range could be triggered by earthquake activity, especially when the poorly consolidated units are water saturated. Tree-ring analyses indicated reactivation of landslides in the southern Gravelly Range/Madison Valley/Madison Range area, in response to the 1959 Hebgen Lake, 1973 Yellowstone Park, and 1983 Borah Peak earthquakes (O'Neill et al., 1995).

Individual Stratigraphic Sections

Four sets of exposures were identified for which schematic stratigraphic sections could be drawn, showing the mutual relations, age limits and lithologies of the post-Laramide deposits (other than the Huckleberry Ridge Tuff). Other exposures of post-Laramide strata support the physical stratigraphy and age assignments shown for these localities.

Exposures at Black Butte

The landslide scarp just west of Black Butte exposes the gravel of Black Butte (as discussed previously), resting on a dip slope of Muddy Formation and overlain by tuffaceous mudstones of the Renova Formation. The thickness for the Renova Formation shown in figure 14 is based partly on better-exposed outcrops around the periphery of Black Butte. The Renova Formation is locally overlain by remnants of a mafic tan tuff sourced from the Black Butte volcanic center (Gutmann et al., 1989).

Exposures at Lion Mountain

The thickest section of Renova Formation in the Gravelly Range is exposed particularly well on the west side of Lion Mountain (Fig. 15). The Renova Formation rests on uppermost limestones of the Madison Group, which show a few thin traces of red basal Amsden Formation siltstones remaining on them. The Renova Formation sedimentary sequence is capped by basalt flows from the Lion Mountain volcanic center.

Exposures at Red Hill/Lazyman Hill

The gravel of Black Butte lies on folded Mesozoic rocks at Red Hill and the adjacent southern margin of Lazyman Hill. The gravel apparently grades conformably upward into the siltstone, limestone and conglomerate of Red Hill, based on the observation of small lenticular deposits of the gravel in the lower parts of the intertonguing siltstones and limestones exposed at the south end of Lazyman Hill. A very small patch of Renova tuffaceous mudstones is also present on the south edge of Lazyman Hill (Fig. 16).

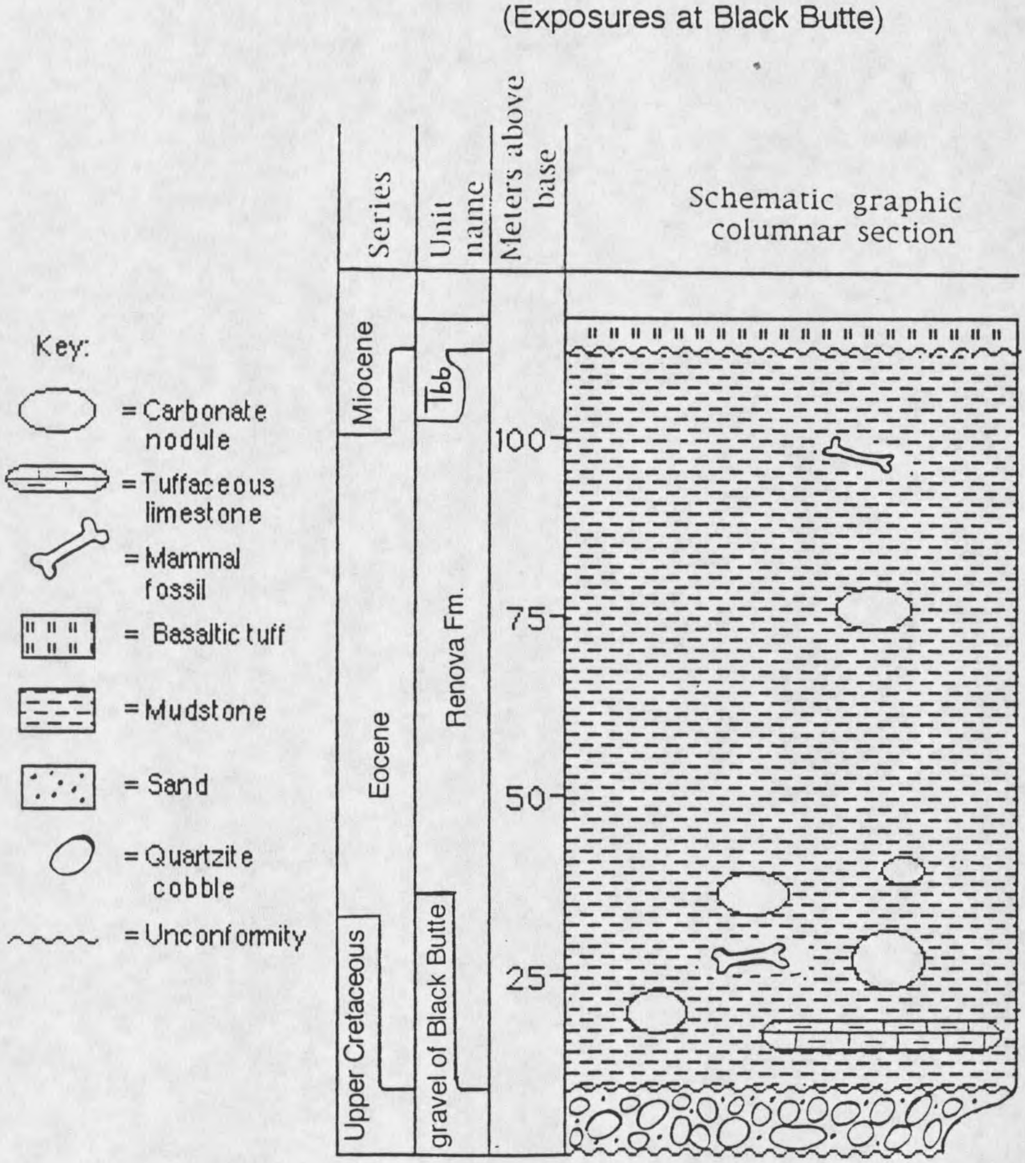

Figure 14. Schematic stratigraphic section (not actually measured) compiled from exposures near the western side of Black Butte. Tbb = tuff facies of basalt and phonolite of Black Butte.

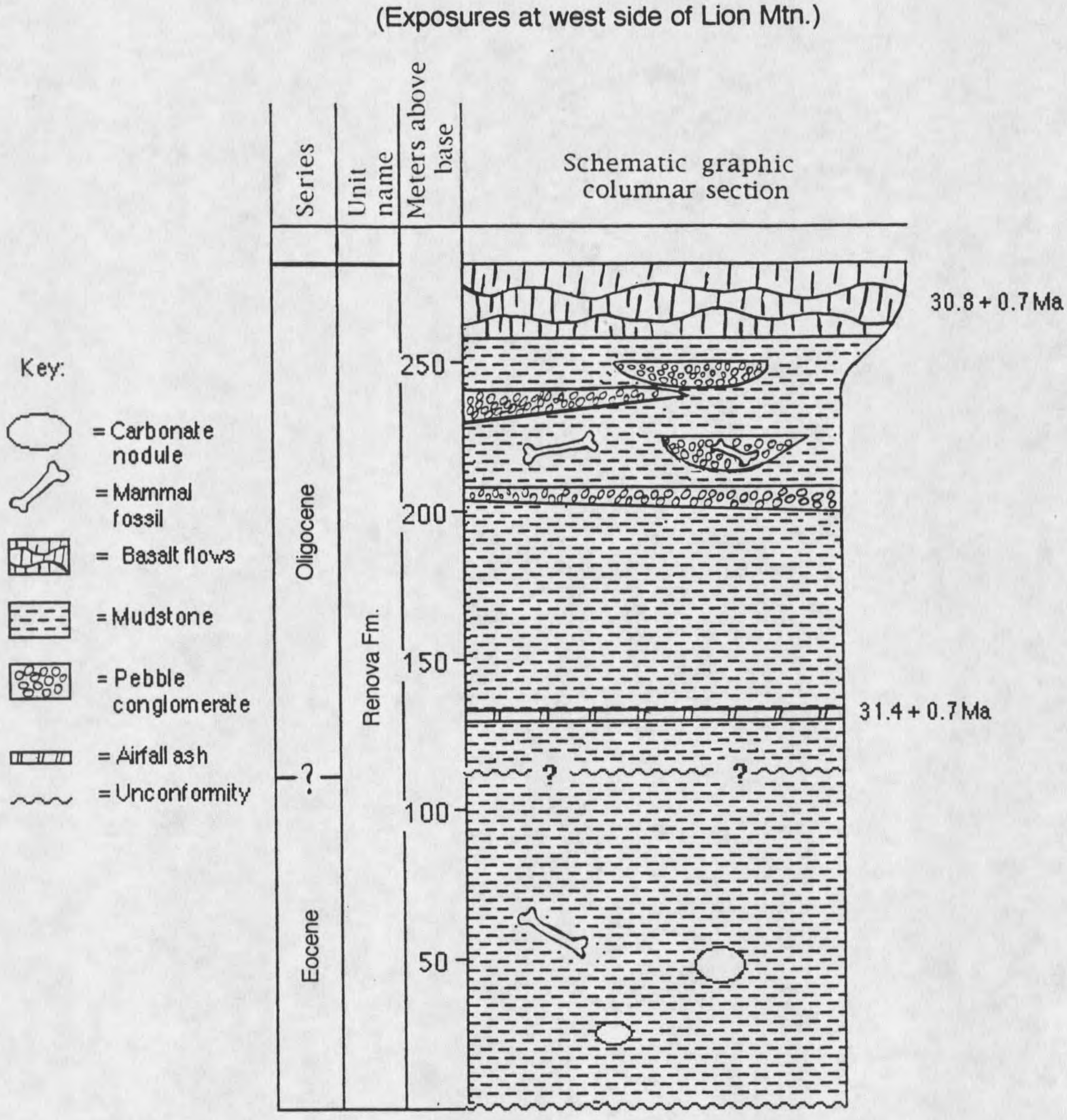

Figure 15. Schematic stratigraphic section (not actually measured) for exposures at the eastern side of Lion Mountain. Radiometric dates from Gutmann et al. (1989).

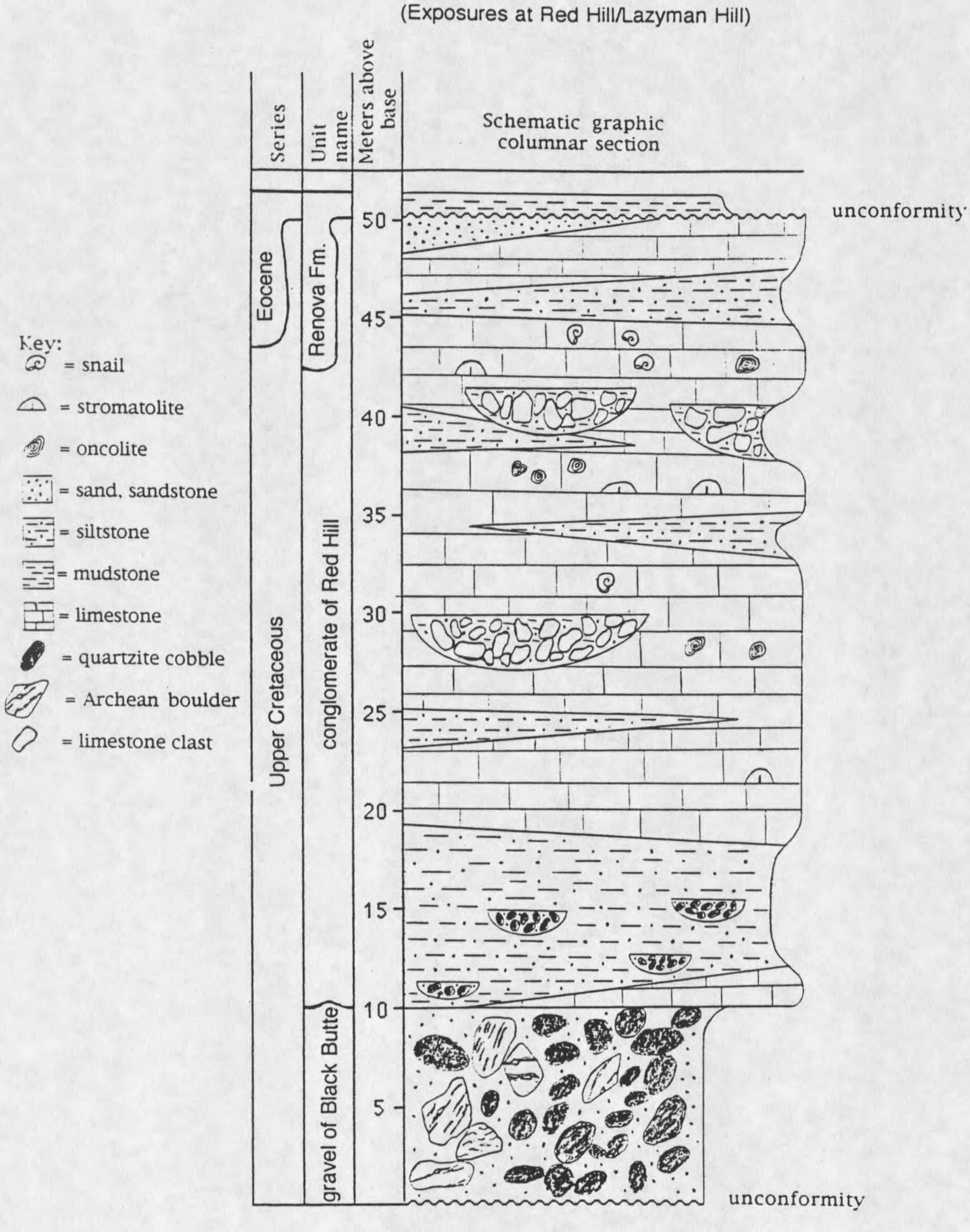

Figure 16. Schematic stratigraphic section (not actually measured) for exposures in the Red Hill/Lazyman Hill area of Monument Ridge.

Exposures at Tepee Mountain

Tepee Mountain forms the eastern margin of Tepee basin, between slightly higher adjacent peaks exposing Shedhorn Sandstone. Here, thin deposits of the gravel of Black Butte and the conglomerate of Red Hill are overlain by fossiliferous Renova Formation mudstones and basalt flows from local vents (Fig. 17).

Generalized Stratigraphic Column

Observations from the four localities shown in figures 14-17, and from the outcrop of Huckleberry Ridge Tuff, along with mammalian biostratigraphic age control, provide sufficient information to compile a generalized Late Cretaceous through Tertiary stratigraphic column for the southern Gravelly Range. This can be compared to the results for southwestern Montana basins (Plate 2). Because of the recent changes in time scale calibration (Cande and Kent, 1992; Prothero and Swisher, 1992) it was necessary to choose which geochronologic datum plane to line up between the results from this study and those of Fields et al. (1985). Because one of the major points of plate 2 is to indicate the age equivalence between the base of the Renova Formation in the field area and the base of the Renova Formation in the modern intermontane basins (see Structural Disruption of the Renova Formation, p. 76), the Uintan/Duchesnean boundaries of the two schemes are lined up horizontally; other temporal boundaries may not coincide.

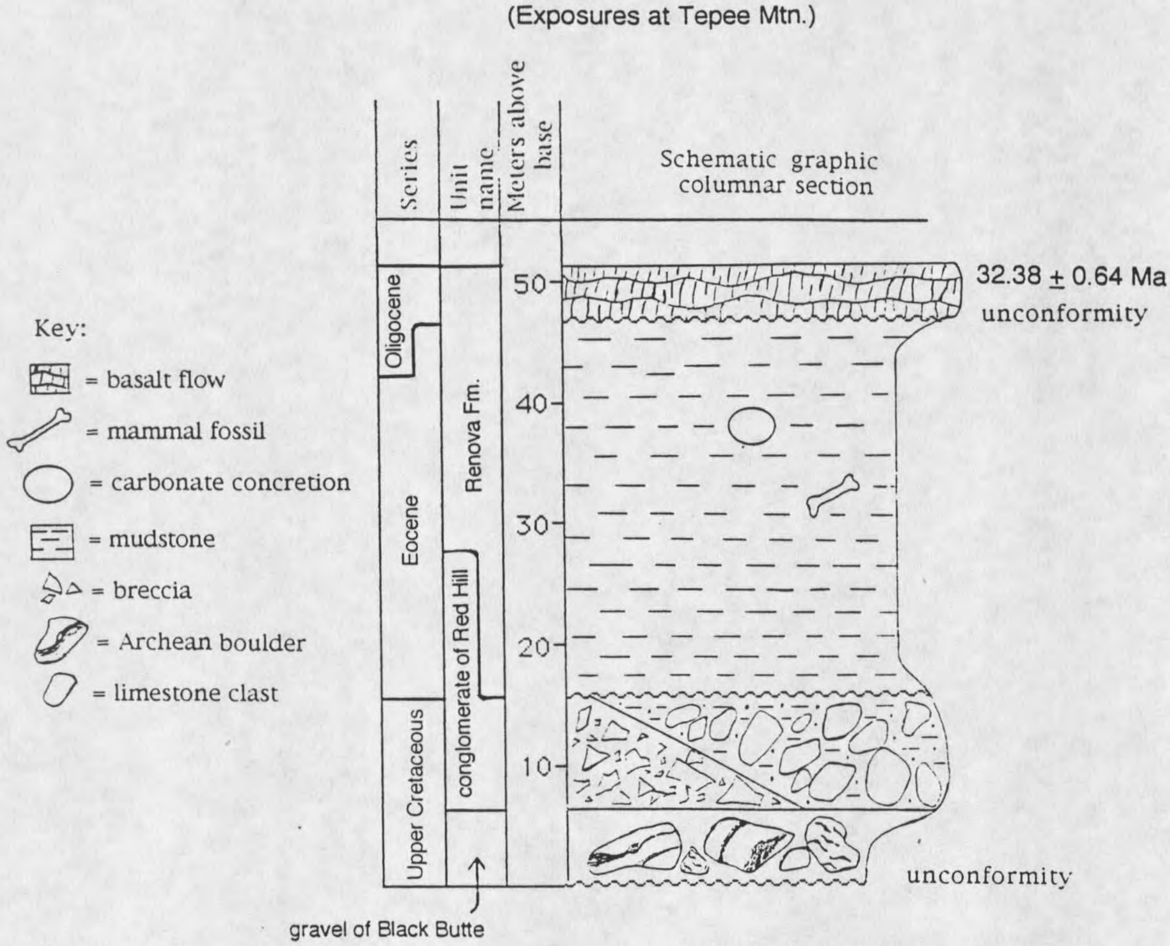

Figure 17. Schematic stratigraphic section (not actually measured) for Tepee Mountain, including radiometric date for basalt flow at top (see Appendix).

VERTEBRATE PALEONTOLOGY OF THE RENOVA FORMATION

Mammalian Biochronology

Vertebrate paleontologists were among the first workers to investigate the Tertiary clastic rocks of western Montana basins. They noted the strong similarity, both lithologically and in terms of shared faunal elements, of localities such as Pipestone Springs (Jefferson basin) and the Canyon Ferry area (Townsend basin) to the White River Group of the northern Great Plains (Douglas, 1901; Matthew, 1903; Osborn, 1909; White, 1954). In reference to these and other late Eocene to Oligocene localities in western Montana basins, early publications often used terms such as "*Titanotherium* beds" or "*Oreodon* beds," first developed as basic biostratigraphic subdivisions of the White River Group strata.

The early recognition of the utility of mammalian biostratigraphic range-zones as a means of correlating Cenozoic continental sections ultimately led to a biochronology based in North America: the North American Land Mammal Ages (NALMA). These were first formalized as the "North American Provincial Ages" by the Wood Committee (Wood et. al., 1941), and the ongoing effort since that time has been to: (1) free them from the lithostratigraphic criteria which were originally mixed in with biostratigraphic criteria; (2) more clearly define their temporal boundaries such that they neither overlap nor leave a gap; (3) add to the database of taxa and their associated range-zones, from which the biochronology is generated; (4) more accurately correlate the NALMA with the other time scales in widespread use for the Cenozoic.

Despite disagreements between authors regarding some NALMA definitions, they are extremely useful in discerning intervals of Cenozoic time. In general, even with the advent of modern radiometric dating techniques and the use of magnetic polarity stratigraphy, mammalian biostratigraphy has the potential to resolve finer time increments within the Paleogene than any other geochronologic method (Flynn, et. al., 1984; Woodburne, 1987).

Ongoing debate centers on the validity and defining criteria of some NALMA, particularly the Duchesnean. The recent redefinition and faunal characterization of the Duchesnean by Lucas (1992) is primarily followed here.

Calibrations of the NALMA with respect to other time scales, such as the epochs, the magnetic polarity time scale, and the numerical time scale, are subject to shifts as new or corrected data become available. Unfortunately, NALMA have often been used in the geological literature as if they were subdivisions of the epochs, despite the fact that the epochs are defined in Europe on entirely different criteria. Since the epochs are in such widespread use, it is important to clearly state which time scale calibration is being used, although as Emry et al. (1987) put it, "As long as one is considering only the mutual temporal relationships of North American units, where the Eocene-Oligocene boundary is drawn is irrelevant".

Figure 18 shows the recent recalibration of part of the Paleogene time scale (Duchesnean through Whitneyan interval) relevant to this research project (Prothero and Swisher, 1992). The major features of this revision include the much shorter duration of the Chadronian, and its shift from primarily early Oligocene entirely into the late Eocene, with the Chadronian-Orellan and

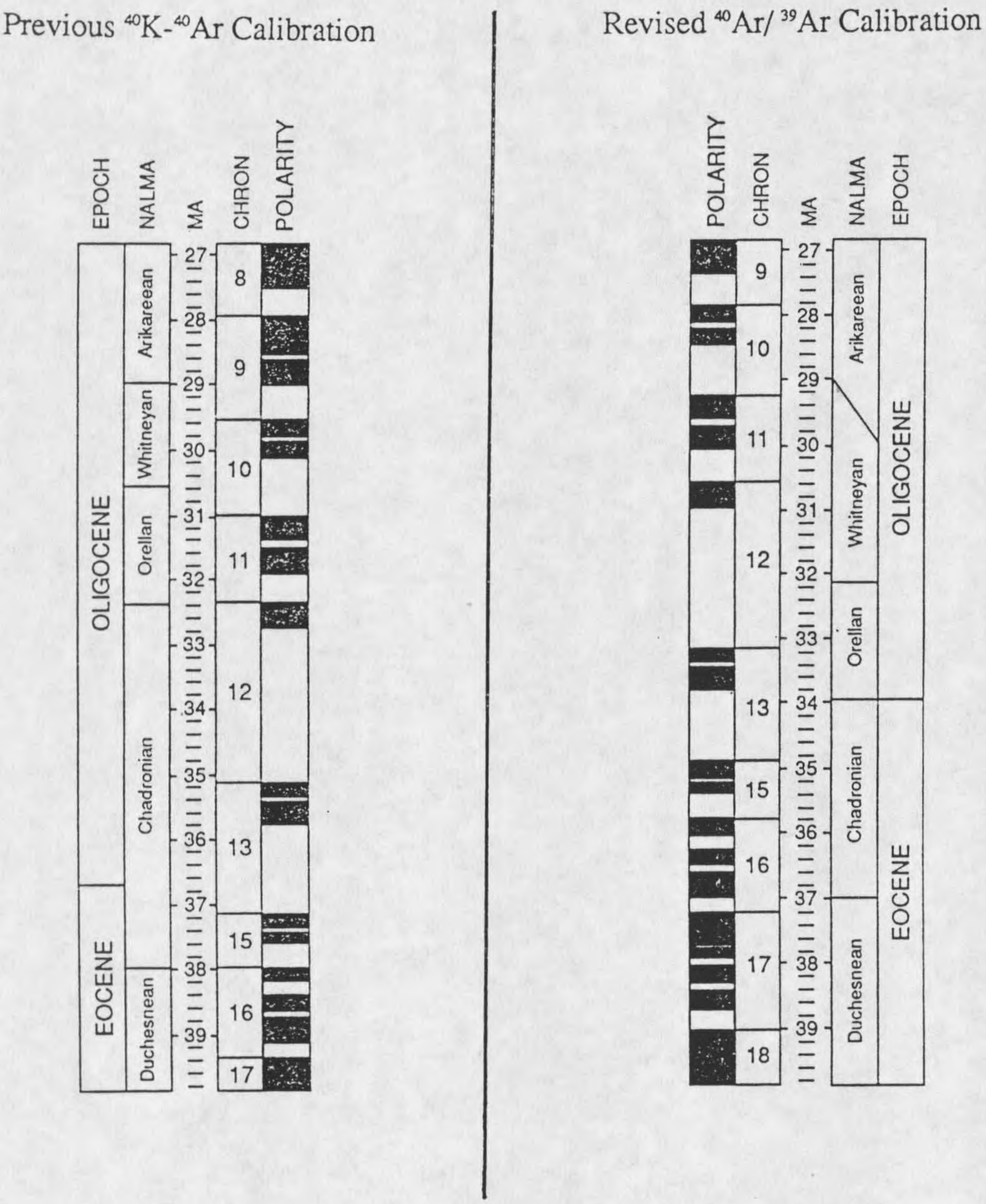

Figure 18. Calibration of the Duchesnean through Arikareean chronology in North America. Calibration based on Evernden et al. (1964) and Berggren et al. (1985) shown on left. New correlation shown on right (modified from Prothero and Swisher, 1992).

Eocene-Oligocene boundaries nearly coinciding at about 34 Ma. This shift produces the need to 'translate' the statements of some earlier authors regarding the epochs correlated with a particular mammal fauna. For instance, in the Gravelly Range, Mann (1954, 1960) asserted that fossils from the mudstone exposures near Black Butte indicated an early Oligocene age; those fossils now indicate a late Eocene age.

Paleontology of the Field Area

The stratigraphically highest and lowest exposures of Renova Formation sedimentary rocks within the field area are given age limits based on mammalian fossils collected by: (1) Mann (1954) and identified by G. L. Jepsen; (2) A. Lewis and others from Harvard University's Museum of Comparative Zoology (in 1952 and 1958); (3) M. C. McKenna and associates from the American Museum of Natural History; and (4) the author and J. M. O'Neill during this study and curated at the American Museum of Natural History.

These sources were combined to form taxonomic lists (Table 1) for four localities within the field area (Fig. 19).

Table 1. Taxonomic Lists for Localities in the Field Area

Upper Lion Mountain Locality

Marsupialia
- Didelphidae
  - Copedelphys stevensoni
  - Nanodelphys sp.

Table 1. (continued)

Insectivora
    Talpidae
        gen. & sp. indet.

Lagomorpha
    Leporidae
        Palaeolagus cf. burkei

Rodentia
    Heteromyidae
        Indet. Heteromyine
    Cricetidae
        Leidymys sp.

Carnivora
    Canidae
        Hesperocyon sp.
        Oxetocyon sp.

Perissodactyla
    Rhinocerotidae
        Diceratherium Tridactylum

Artiodactyla
    Agriochoeridae
        gen. & sp. indet.
    Merycoidodontidae
        gen. & sp. indet.
    Hypertragulidae
        Hypertragulus sp.
    Leptomerycidae
        Leptomeryx sp.

Tepee Mountain Locality

Lagomorpha
    Leporidae
        ?Megalagus sp.

Rodentia
    Eomyidae
        Protadjidaumo sp.

Table 1. (continued)

Creodonta
    Hyaenodontidae
        Hyaenodon sp.

Perissodactyla
    Titanotheriidae
        gen. & sp. indet.

Black Butte Locality
MCZ = collected by A. Lewis, curated at Harvard
Mann = reported by Mann (1954)

Carnivora
    Felidae
        gen. & sp. indet. (MCZ)

Perissodactyla
    Helaletidae
        gen. & sp. indet. (MCZ)
    Titanotheriidae
        gen. & sp. indet. (Mann)
    Hyracodontidae
        Hyracodon sp. (MCZ)

Artiodactyla
    Agriochoeridae
        Protoreodon sp.
    Leptomerycidae
        Leptomeryx sp. (MCZ; Mann)

Rapamys Site
MCZ = collected by A. Lewis, curated at Harvard

Rodentia
    Paramyidae
        Rapamys sp.
    Cylindrodontidae
        Pareumys sp. (MCZ)

Carnivora
    gen. & sp. indet.

Artiodactyla
    Agriochoeridae
        Protoreodon pearcei (MCZ)

Figure 19. Paleontologic index map showing the Tepee Creek locality (**T**), Black Butte locality (**B**), *Rapamys* site (**R**), and upper Lion Mountain locality (**L**).

Fossils from three of the localities, 'Tepee Mountain locality', 'Black Butte locality' and '*Rapamys* site', were collected from the basal tuffaceous mudstone of the Renova Formation preserved on the range crest. The stratigraphically highest fossiliferous sedimentary strata in the field area are the 'upper Lion Mountain' exposures, within 25 meters of the basalt flows capping the summit (Fig. 20). The taxa from this locality indicate a Whitneyan age (Gutmann et al., 1989). The Whitneyan NALMA is presently calibrated at about 29 to 32 Ma (Prothero and Swisher, 1992); this age range agrees well with radiometric dates bracketing this locality: 31.4 $\pm$ 0.7 Ma for an underlying airfall ash, and 30.8 $\pm$ 0.7 Ma for the overlying basalt flows (Gutmann et al., 1989). Since no significant additions to the upper Lion Mountain fauna have been made since Gutmann et al. (1989), its fauna and age brackets will not be discussed further.

The biochronologically significant taxa from each of the three sites representing the base of the Renova section can be used to constrain the age range of each site in terms of the North American Land Mammal Ages. The ranges of the taxa discussed below are compiled primarily from the syntheses contained in Emry (1981, 1992), Krishtalka et al. (1987), Emry et al. (1987), and Lucas (1992).

Tepee Mountain Locality

This set of exposures has seen little, if any, collecting prior to this study. The thin (10-30 m-thick) section of cream-colored tuffaceous mudstone is pierced by a small vent of scoriaceous agglomerate and overlain by a basalt flow dated at 32.38 $\pm$ 0.64 Ma (Appendix).

Carbonate concretions are numerous here, as elsewhere in the basal Renova Formation. One of the concretions yielded a juvenile creodont skull,

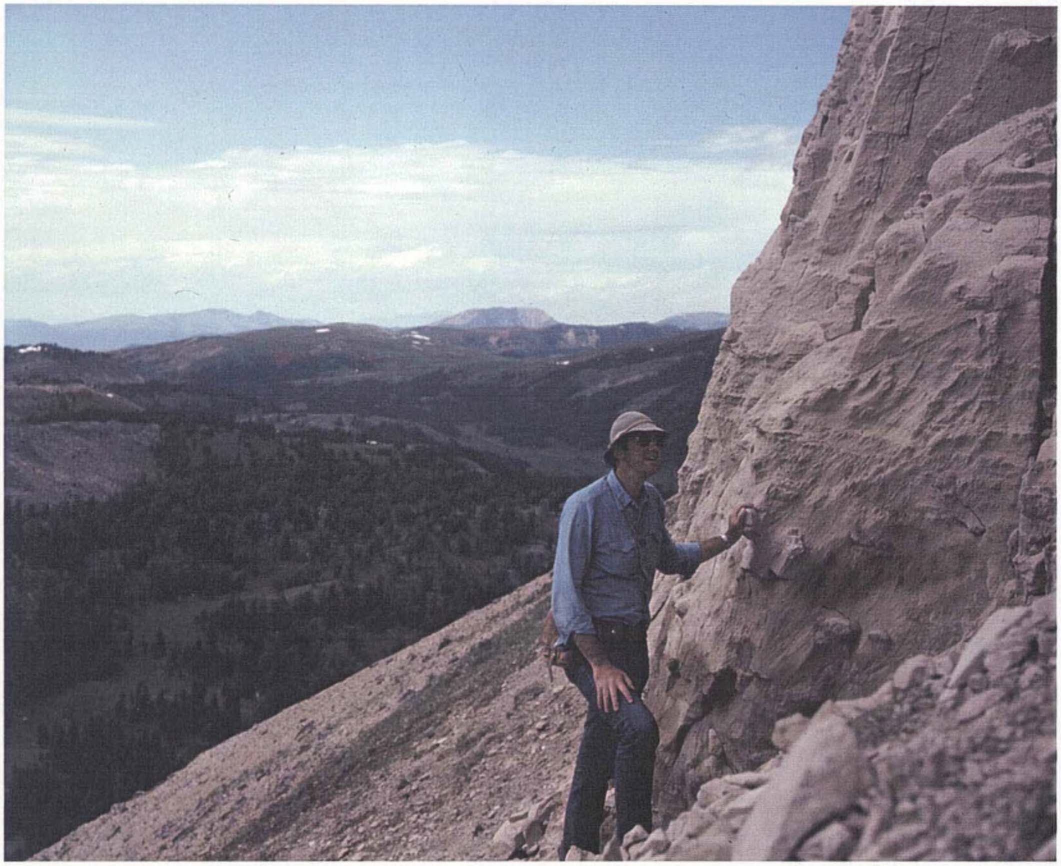

Figure 20. Renova Formation mudstones, sandy siltstones, and thin granule-pebble conglomerate layers which produce a Whitneyan fauna, upper slope of Lion Mountain. This locality is bracketed by an underlying air-fall ash dated at 31.4 $\pm$ 0.7 Ma and an overlying basalt flow dated at 30.8 $\pm$ 0.7 Ma (Gutmann et al., 1989); this serves as a confirming instance of the numerical calibration of the Whitneyan NALMA shown in figure 21.

identified as *Hyaenodon.* This specimen, still in preparation at the AMNH (Fig. 21), appears to preserve the most complete example of the milk dentition of this genus (M. McKenna, pers. comm., 1996).

A partial skull of the Eomyid rodent *Protadjidaumo* was also recovered from a concretion (Fig. 22). The temporal ranges of these taxa are shown below:

Table 2. Biochronology of Taxa from the Tepee Mountain Locality

UINTAN	DUCHESNEAN	CHADRONIAN
I-?	---*Protadjidaumo* ----------	---I
	I----*Hyaenodon* -----------	------------------------------->

There is some disagreement in the literature as to whether *Protadjidaumo* first occurs in the latest Uintan (Emry, 1981) or Duchesnean (Lucas, 1992); however, it makes a last appearance by the end of early Chadronian time. *Hyaenodon* is a Eurasian immigrant with a range that passes through four NALMA boundaries, yet its Duchesnean first appearance helps limit the age of the enclosing sedimentary rocks to Duchesnean or early Chadronian.

The Tepee Mountain locality also yielded fragments of turtle postcrania, large weathered bone cores and a single large tooth crown of a titanothere (= brontothere), and two partial skulls and a right dentary fragment of a large primitive lagomorph. The dentary fragment, with moderately worn lower third and fourth premolars and first molar (P_3-M_1), shows a simple P_3 with a single external reentrant (Figure 23), characteristic of the extinct basal subfamily Paleolaginae, as discussed by Dawson (1958). In terms of general size and

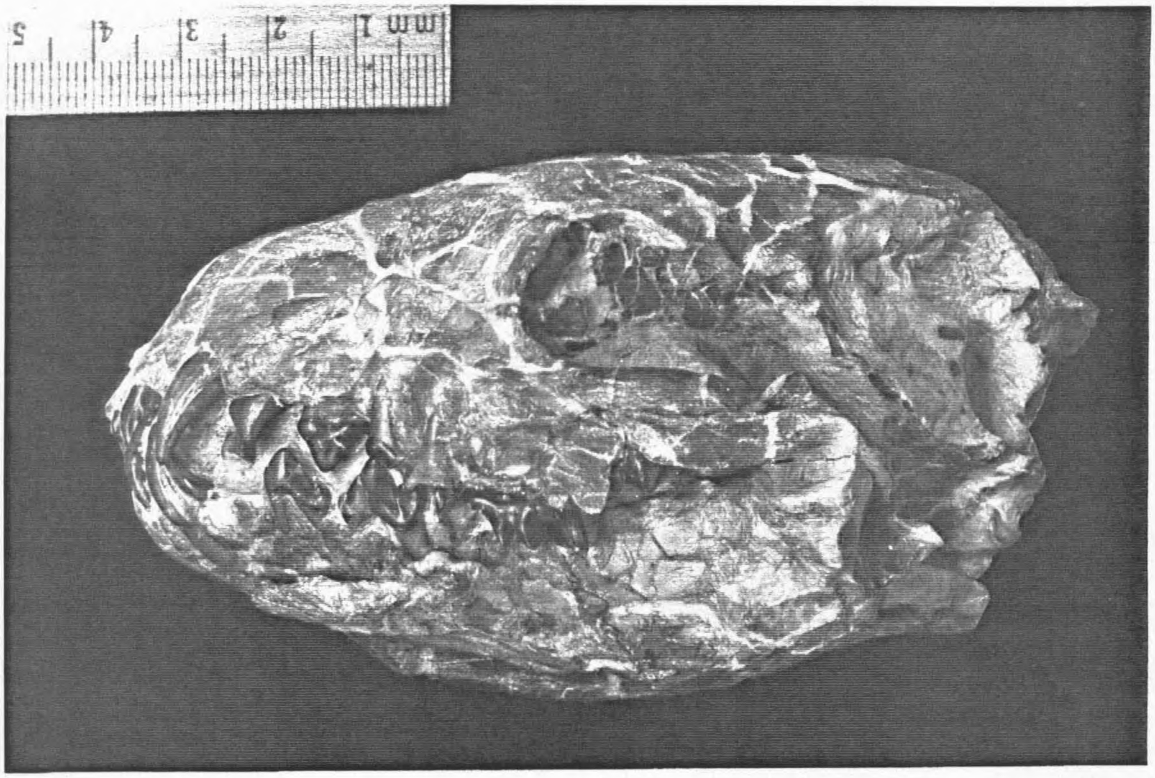

Figure 21. Juvenile *Hyaenodon* skull from the newly described Tepee Mountain locality, showing milk dentition (in preparation- jaws not yet separated). (Courtesy of the American Museum of Natural History).

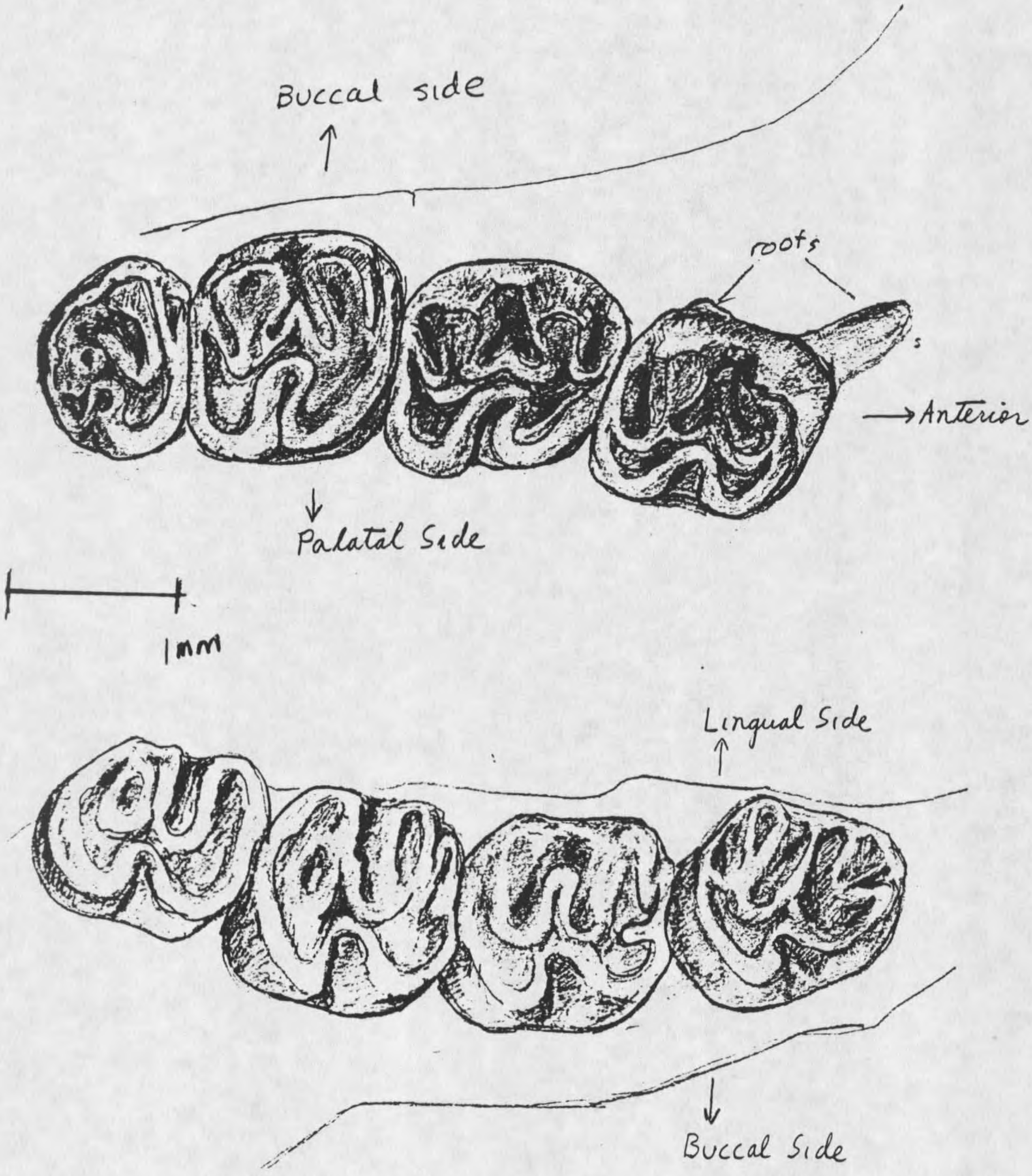

Figure 22. Occlusal views of upper cheek teeth (top), and lower cheek teeth (bottom) of the Eomyid rodent *Protadjidaumo* from the Tepee Mountain locality. (Drawings by Nancy Hong, American Museum of Natural History).

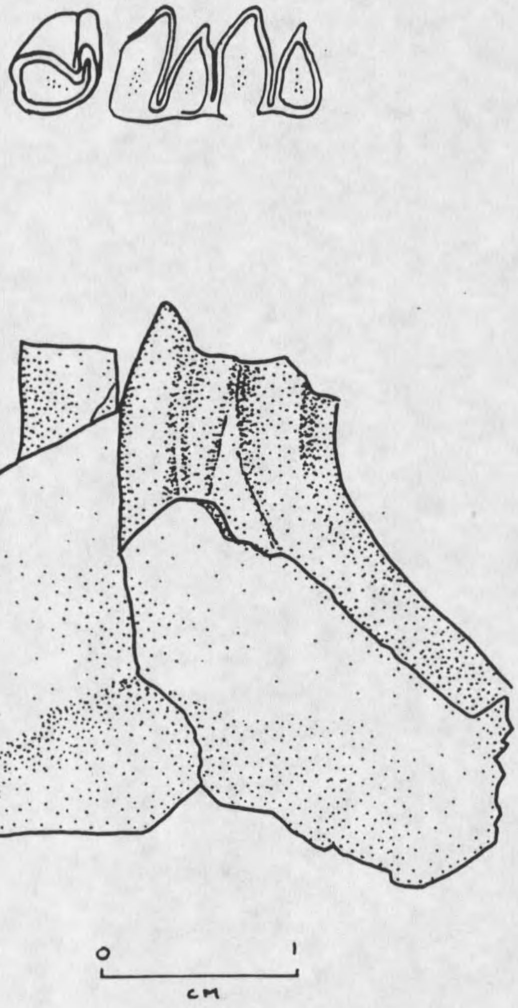

Figure 23. Sketch of right jaw fragment showing P_3-M_1 of a large unidentified lagomorph resembling *Megalagus*, from the Tepee Mtn. locality. Note the relatively simple P_3 morphology (tooth on left), showing a single external reentrant. Outline of teeth in occlusal view (top) and lateral view (bottom). (Drawings by Frankie Jackson, Museum of the Rockies).

primitive dental pattern of the P_3-M_1 and P^3-M^2, the specimens appears to most closely resemble the Chadronian taxon *Megalagus* among the Eocene and Oligocene Leporids in the Frick collection at the AMNH. *Megalagus* is apparently not reported from earlier than the Chadronian, but is closely related to the earlier genus *Mytonolagus*, known from the Uintan. Preparation of the two partial skulls may help resolve whether the specimens can be referred to either of these genera.

Black Butte Locality

Locality data for fauna collected by Mann (1954) noted only that they were from exposures in the vicinity of Black Butte. Collections made by A. Lewis of Harvard (1952 and 1958, unpublished data) included a general map indicating the sample site to be located along the eastern margin of Black Butte. Since the exposures in this area constitute as much as 140 m of poorly consolidated mudstones, there is the possibility of 'contamination' of the basal age estimate by significantly younger fossils from higher in the section. Local slumping of the mudstones may further complicate this problem. The only taxon reliably associated with the basal Renova strata at this locality is the agriochoerid *Protoreodon*, which ranges from the early Uintan into the Chadronian (Krishtalka et al., 1987), although Lucas (1992) notes it as a Duchesnean last occurrence.

Table 3. Biochronology of Taxa from the Black Butte Locality

<table>
<tr><th>UINTAN</th><th>DUCHESNEAN</th><th>CHADRONIAN</th></tr>
<tr><td></td><td>|----Hyracodon -----------</td><td>-----------------------------></td></tr>
<tr><td>|-------------------------------</td><td>----Protoreodon -----------</td><td>---|</td></tr>
<tr><td></td><td>---?---?---?---</td><td>---Leptomeryx ----------></td></tr>
</table>

There seems to be substantial disagreement in the literature about the range of *Leptomeryx*; Emry et al. (1987) note its abrupt Chadronian appearance, whereas its presence did not conflict with the Duchesnean age assignment of a fauna mentioned in Krishtalka et al. (1987, p.105). The Black Butte fauna, with the possibility of contamination noted above, has age limits similar to that of the Tepee Mountain locality, i.e. Duchesnean to early Chadronian.

Rapamys Site

This locality is a small exposure of mudstones only 3-5 meters thick, preserved in a Paleogene paleovalley between Black Butte and Lion Mountain. The sediments here are also cream-colored tuffaceous mudstones containing carbonate concretions, but with an unusual concentration of small (3 mm) cylindrical pellets present in the matrix, interpreted to be fossilized earthworm casts (E. Evanoff, pers. comm. 1996). Relatively complete skulls of *Rapamys* were recovered from this site (Fig. 24). *Pareumys* and *Protoreodon* are also present. In addition to these time-significant taxa, this site yielded a potentially identifiable carnivore jaw and a partial snake skull.

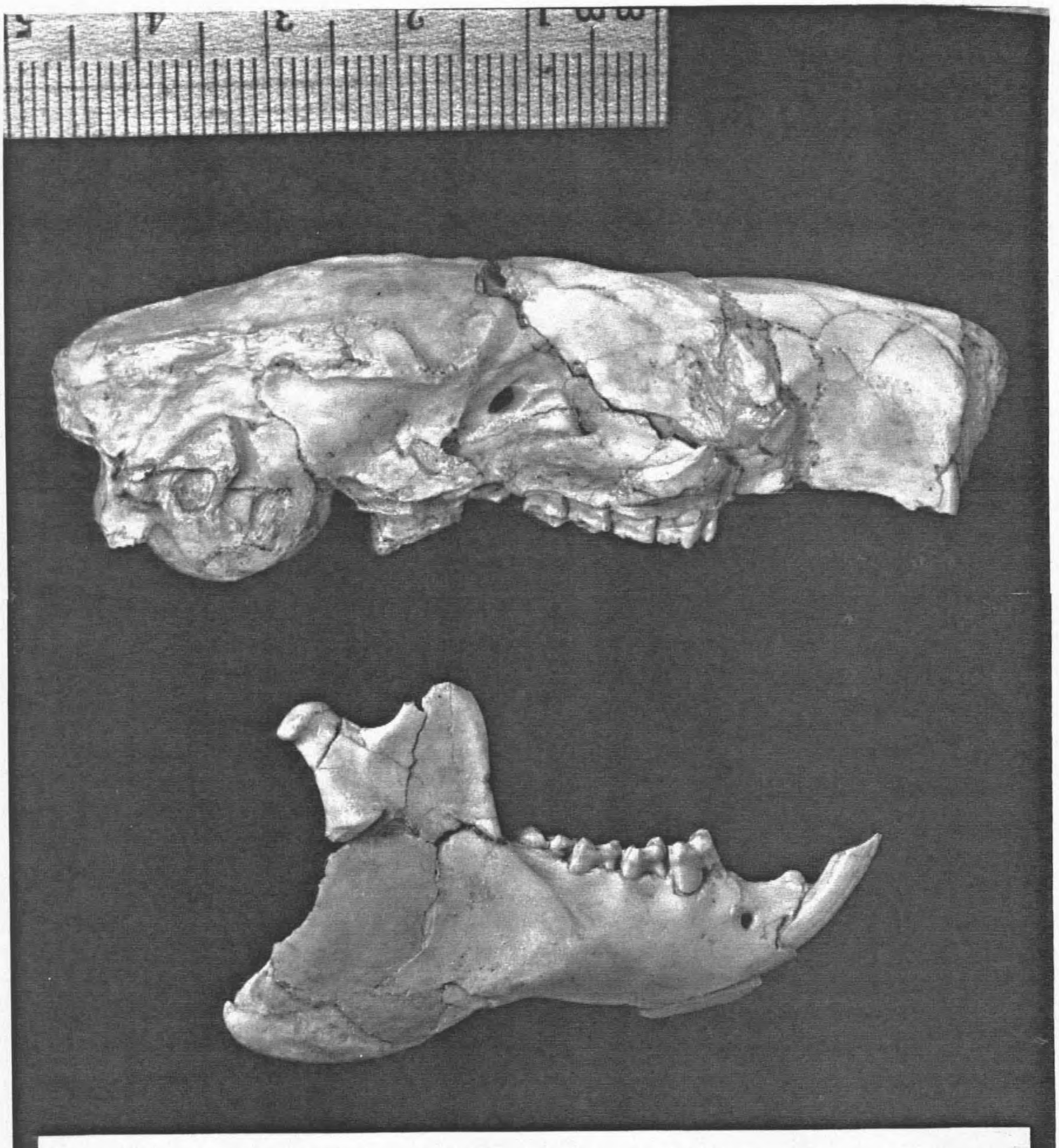

Figure 24. Skull and lower jaw (image reversed) of *Rapamys*, a Duchesnian last occurrence, from the *Rapamys* site. (Photos courtesy of Chester Tarka and Lorraine Meeker, American Museum of Natural History).

Table 4. Biochronology of Taxa from the *Rapamys* Site

UINTAN	DUCHESNEAN	CHADRONIAN
I-?----------------------------	------*Rapamys* ------------I	
I-?-----------------------------	-----*Pareumys* ------------I	
I-------------------------------	----*Protoreodon* ------------	---I

Based on these ranges, this locality could be as old as Uintan, but is clearly no younger than Duchesnean.

Proposed Duchesnean Local Fauna

It is possible that the base of the mudstone is time-transgressive over a small distance, i.e. that the *Rapamys* site is significantly older than the other localities. However, the simplest hypothesis consistent with the paleontological data is that the taxa from the three localities constitute a Duchesnean local fauna present at the base of the Renova section, and that deposition of these mudstones therefore began between 37 and 40 Ma (Prothero and Swisher, 1992).

Because of the largely unfossiliferous nature of the Duchesne River Formation on which the Duchesnean NALMA was based, the principle correlatives of this "type area" have contributed the majority of mammalian genera known from this NALMA. The heavy reliance on widely geographically separated local faunas is the source of some uncertainty, especially regarding which local faunas should be included in the Duchesnean and which should be subsumed in the early Chadronian (see discussions in Emry, 1981; Emry et al., 1987). Given these difficulties, the local fauna of this report may, with continued collecting, contribute to the faunal characterization of the contentious Duchesnean interval.

TECTONIC HISTORY AND DISCUSSION

The most likely geologic history of the Gravelly Range consistent with the available data in the literature and from this study, begins with Late Cretaceous uplift of the area as the western limb of the Madison-Gravelly arch, with syn- and post-tectonic erosion of the arch. Far-traveled quartzite cobbles, most likely from a southwestern thrust belt source (see Ryder and Scholten, 1973) or possibly a northwestern thrust belt source (Pioneer Mountains according to Ruppel, 1993), onlapped the western edge of the erosionally beveled arch in Late Cretaceous time (Fig. 25A). Features of the gravel deposit west of Black Butte suggest that some of the deposition involved mass-movement mechanisms (Gutmann, et al., 1989). More proximally sourced Archean metamorphic cobbles and boulders from an unroofed foreland structural culmination, probably the Blacktail-Snowcrest arch, mixed locally with the quartzite clasts. Major uplift of the Blacktail-Snowcrest arch took place several Ma earlier than the Madison-Gravelly arch (Perry et al., 1992), and could have provided a source for basement lithologies prior to the end of Laramide fault movement in the field area. Conformable transition to deposition of dominantly Paleozoic limestone clasts with some Archean basement clasts took place as Lima Conglomerate equivalents (conglomerate of Red Hill) reached the field area from the Blacktail-Snowcrest arch, with the conglomerate facies locally intertonguing with siltstone and freshwater limestone representing lower-energy floodplain and lacustrine depositional environments. Their deposition is

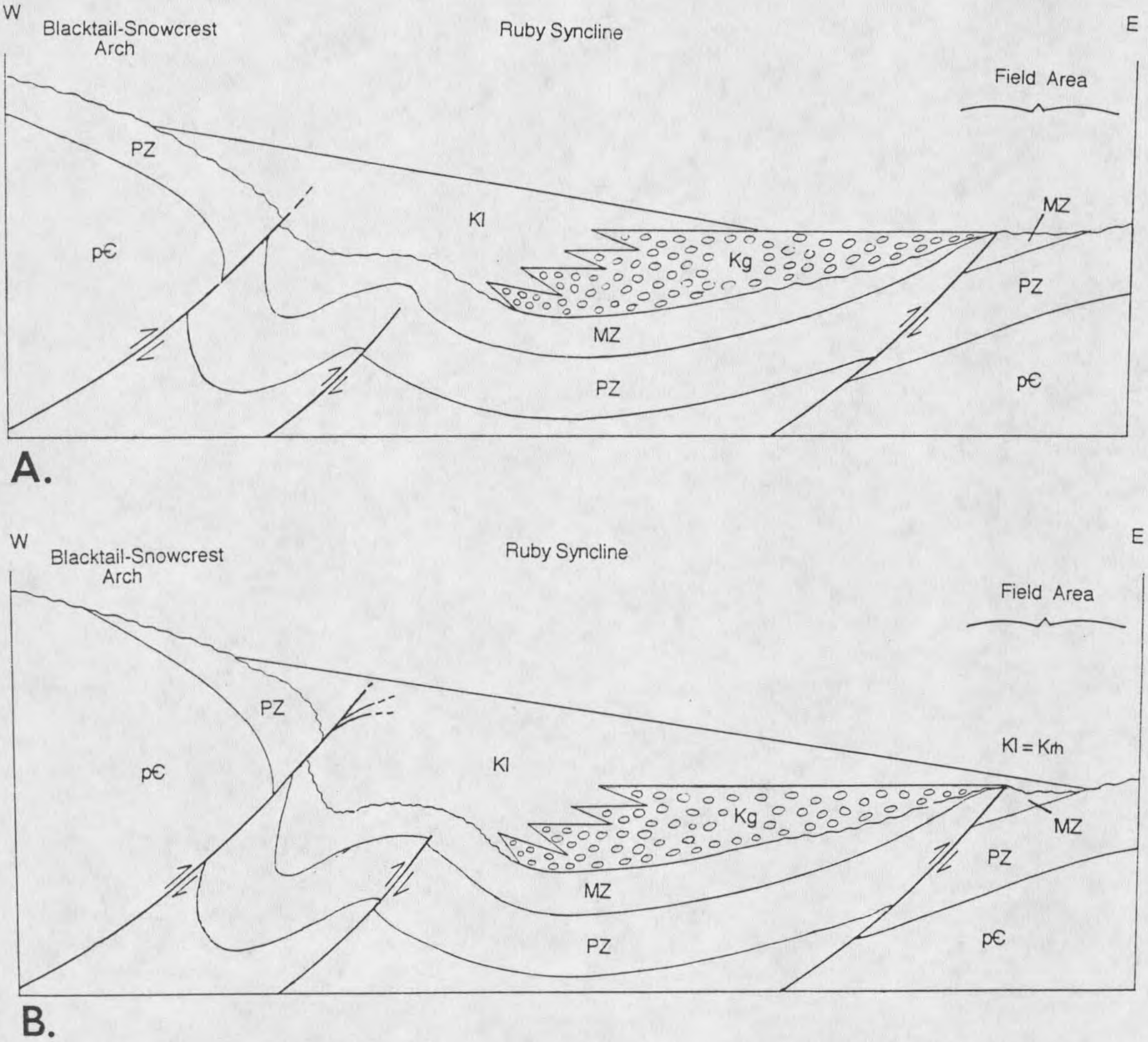

Figure 25. Diagrammatic cross-sections (not to scale) from the eastern side of the Blacktail-Snowcrest arch through the northern part of the field area, showing the proposed Late Cretaceous sequence of tectonic and depositional events. (A) Deposition of gravel of Black Butte derived from a thrust belt source to the southwest (see Ryder and Scholten, 1973), onlapping the western flank of the Madison-Gravelly arch. (B) Deposition of Lima Conglomerate equivalents (conglomerate of Red Hill) derived from the Blacktail-Snowcrest arch just prior to final movement on thrusts in the field area. (pЄ = Precambrian, undivided; PZ = Paleozoic; MZ = pre-Laramide Mesozoic rocks; Kl = Lima Conglomerate; Kg = gravel of Black Butte; Krh = conglomerate of Red Hill).

probably syntectonic, as shown by their slight folding adjacent to a thrust at Lazyman Hill (Fig. 25B). Erosion had cut deeply into the Phanerozoic section of the field area by this time; the limestone conglomerate drops in elevation from west to east, resting on Kootenai sandstone on the west and on upper Madison Group limestone in Tepee basin.

A major erosional episode prior to about 40 Ma is indicated by the unconformity below the Renova Formation. Paleozoic to Lower Cretaceous rocks were exposed in most areas, with some patches of the gravel of Black Butte and conglomerate of Red Hill remaining by the beginning of mudstone deposition at 40-37 Ma. In those places where the Renova overlies the gravel of Black Butte and conglomerate of Red Hill, there is no evidence of intertonguing. If the conglomerate of Red Hill is correlative with the Campanian Lima Conglomerate (Nichols et al., 1985), as proposed, the unconformity above the conglomerate of Red Hill and below the Renova Formation represents a gap of about 38 million years. A minimum estimate of this time gap is 28 million years, based on the slight deformation of the unit by a thrust fault and the 68 Ma upper age limit for Laramide contraction of the Madison-Gravelly arch (Tysdal et al., 1986).

The possibility of conformable relations between the conglomerate of Red Hill and the Renova Formation should be considered. A number of enigmatic 'red conglomerates' have been identified in several basins of western Montana, with gradational relations between them and overlying fine-grained Renova Formation strata reported in the Three Forks basin (Robinson, 1963; in Fields et al., 1985), North Boulder basin, lower Ruby River basin and Beaverhead basin (Fields et al., 1985). This raises the possibility that the limited exposures of the contact may prevent recognition of interbedded, conformable relations, and that the slight folding of the older unit at Lazyman Hill is due to Cenozoic deformation of some sort. In this scenario, the conglomerate of Red Hill would be upper Eocene. Previous workers in the Gravelly Range assigned Paleocene to Oligocene ages to the quartzite-rich gravel, limestone conglomerate and mudstone of the Gravelly Range as shown below:

Table 5. Previous age assignments for the syn- and post-Laramide rocks of this report

	Mann (1954;1960)	Hadley (1980)	Gutmann et al. (1989)	Ruppel (1993)
tuffaceous mudstone	early Oligocene	early Oligocene	Chadronian-Whitneyan (Oligocene)	early to middle Oligocene
limestone conglomerate	Paleocene	"Sphinx" (age uncertain)	N/A	N/A
quartzite gravel	middle to late Eocene	Eocene to early Miocene	Late Cretaceous	early Oligocene

The following factors should be noted with regard to this summary of age assignments: 1) Mann (1960) essentially correlated his limestone conglomerate (= conglomerate of Red Hill) with the Lima Conglomerate by stating that, "...fanglomerate deposits were developed along the front of the rising mass of the Snowcrest Range overthrust to the west" although he believed the conglomerate to be Paleocene and also older than the gravel of Black Butte; 2) some of the age assignments based on mammal faunas would now be "late Eocene" rather than "early Oligocene" due to recalibration (Prothero and Swisher, 1992); 3) Hadley (1980) investigated deposits in the northern part of the Gravelly Range. His descriptions of deposits overlying a widespread erosion surface closely match those of this report and the gravel and sedimentary rocks are presumed to be correlative.

The conclusions of Mann (1954; 1960), Hadley (1969b; 1980) and Ruppel (1993) differ in their age assignment for the conglomerate of Red Hill by about 38 Ma relative to the conclusions presented here. The Campanian age assignment given in this report is potentially testable through collection of palynomorphs from the lacustrine limestone facies of the conglomerate of Red Hill; it would not be hard to distinguish a Late Cretaceous from a late Eocene to Oligocene palynomorph assemblage. Additionally, a femur, tibia and fibula found in the lacustrine limestone appear to be those of a pterosaur (D. Varicchio, pers. comm., 1997), which would rule out a post-Cretaceous age for the conglomerate of Red Hill. Acid preparation may allow more certain identification of this specimen.

No information was obtained in this study to distinguish a tectonic versus climatic mechanism for the shift from erosion to deposition in the early late Eocene. Thompson et al. (1981) argued for a mechanism of rapid climate change from a middle Eocene wet interval to a late Eocene arid or semi-arid interval in southwestern Montana, in which sediment production overwhelmed the carrying capacity of the streams, resulting in aggradation. Numerous lines of paleoclimatic evidence indicate global cooling and increased aridity in a number of 'steps' from the middle Eocene to early Oligocene (Berggren and Prothero, 1992). Within this interval, the most dramatic turnover in North American terrestrial fauna marks the Uintan/Duchesnean transition. At this time, animals and plants adapted to warm climate and tropical forests were decimated by a major shift to a cooler dryer climate (Berggren and Prothero, 1992; Wolfe, 1992). Deposition of the Renova Formation in the field area began at 40-37 Ma, apparently shortly after these dramatic climatic and faunal changes.

The area experienced some erosion of older Renova strata just prior to 32 Ma, but remained a site of deposition, receiving basaltic volcanics and sediment until at least 30 Ma. Some erosion of the Renova cover had taken place by the time eruptions began at Black Butte at 22.9 $\pm$ 1.2 Ma (Marvin, 1974; Gutmann et al., 1989). Timing of subsequent Tertiary deformational and depositional events in the field area is poorly defined. If any strata younger than middle Oligocene were deposited, they were eroded prior to 2 Ma when the Huckleberry Ridge Tuff was emplaced. The dense welding of the tuff at 2,926 m (9,600 ft) in the field area probably rules out surge to up a major topographic slope during its emplacement, as discussed previously. This suggests that much of the 1,100 m of relief on the tuff between the field area and the southern Madison Valley, only 20 km to the east, is due to Quaternary movement on extensional faults bounding the eastern side of the Gravelly Range. Essentially the same conclusion was arrived at based on outcrops of Huckleberry Ridge Tuff further south in the range (O'Neill et al., 1995). High-elevation (2,700-2,900 m) outcrops of Huckleberry Ridge Tuff are found in other ranges within the Yellowstone crescent of high terrain, including the Madison and Gallatin ranges (data of R. L. Christiansen, cited in Pierce and Morgan, 1992), indicating that the structural and physiographic differentiation of contemporary ranges and basins across southwestern Montana may be quite young (< 2.0 Ma).

Structural Disruption of the Renova Formation

Two possible models to account for deposition of fine-grained Renova Formation strata on the crest of the Gravelly Range and in surrounding basins are shown diagrammatically in figure 26. The model shown in figure 26A shows sediments progressively filling basins already delineated, onlapping and finally burying the Gravelly Range. This scenario requires that the basal Renova Formation of the Gravelly Range be younger than that in the adjacent basins. Figure 26B shows deposition of a Renova "blanket" (Thompson et al., 1981; Fritz and Sears, 1993) across a generally low-relief broad basin in which the location of the Gravelly Range is not significantly higher than surrounding areas, followed by offset via extensional faulting after deposition. This scenario requires that the basal Renova Formation of the Gravelly Range be the same age as that in the adjacent basins.

The oldest date for any Renova Formation equivalents overlying the regional Eocene unconformity in southwestern Montana is late Uintan or Duchesnian, assigned to exposures in the upper Ruby basin just west of the Gravelly Range (Plate 2). This Uintan or Duchesnean age is based on the presence of a small species of *Protoreodon* low in the Climbing Arrow Member of the Renova Formation (Monroe, 1976; unpublished data of Tabrum cited in Fields et al., 1985). The fauna reported there is not necessarily older than the Duchesnian fauna reported here for the field area (which also includes *Protoreodon*). Duchesnean local faunas are reported from the Three Forks basin, lower Ruby basin, and Beaverhead basin (summarized in Fields et al., 1985) (Plate 2). All other age determinations, radiometric or paleontologic, for the Renova Formation are younger than these. Based on this, model A of

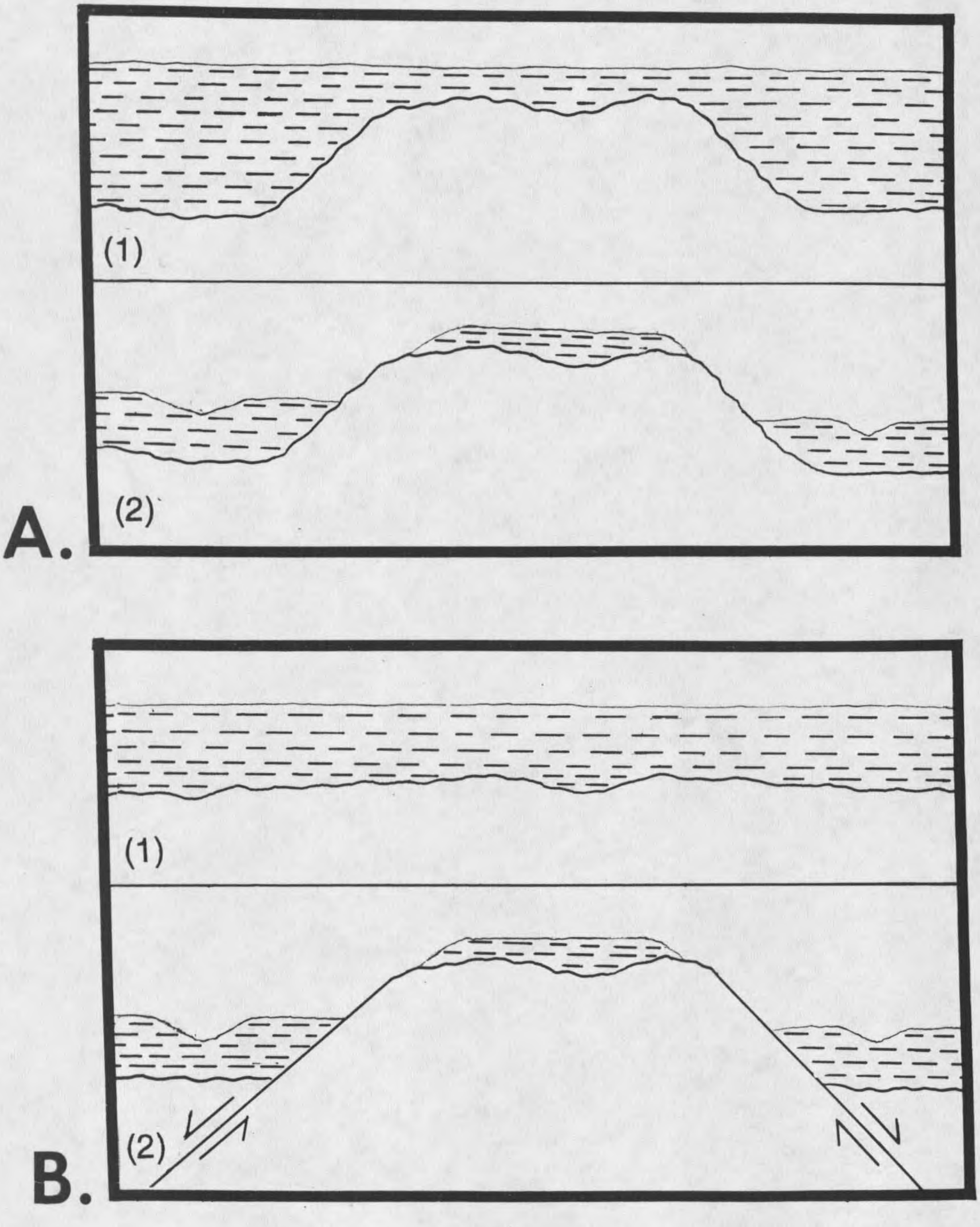

Figure 26. Simplified depiction of two possible models for Eocene-Oligocene deposition of fine-grained Renova sediments on top of the Gravelly Range and in surrounding regions. (A) Progressive filling of already-delineated basins, ending with burial of the Gravelly Range crest (1), followed by erosion (2). (B) Deposition within a broad low-relief basin (1), with subsequent extensional partitioning of the Renova "blanket" (2).

figure 26 can be ruled out as a scenario for deposition of the Renova Formation. Rather, when aggradation began after the middle/late Eocene transition, the Gravelly Range was at an elevation similar to any known areas of Renova Formation deposition in the region. The basin floor now exposed on the crest of the Gravelly Range was not offset relative to adjacent areas until after deposition of the upper sediments of Lion Mountain (about 30 Ma), and possibly not until much later.

Similar extensional disruption of Renova Formation equivalents was noted in the Big Belt Mountains and adjacent basins east of Helena (Reynolds, 1979), although the total displacement there is less than a fourth of the magnitude calculated below for the Gravelly Range region. Estimates of the maximum structural offset between the Renova Formation on the Gravelly Range and its equivalents in adjacent extensional grabens are based on thickness of Cenozoic fill inferred from gravitational data (Schofield, 1981; Ruppel, 1993), added to the difference in surface elevations. Offset with the deepest part of the Centennial Valley is inferred to be 2,860-3,780 m (9,400-12,400 ft); offset with the deepest part of the upper Ruby basin is at least 3,400 m (11,200 ft); and offset with the deepest part of the southern Madison basin, only 20 km east of the field area, is about 5,300 m (17,400 ft).

If the regional 16 Ma Hemingfordian unconformity above the Renova Formation marks initial extensional disruption of the Renova basin and foundering of these grabens (Thompson et al., 1981), an average offset rate of 0.33 mm/yr is obtained between the southern Gravelly Range and southern Madison Valley. If the influence of the Yellowstone hot spot is the primary cause of this extension (see Sears et al., 1995), the offset rate is probably closer to 1 mm/yr or more. Evidence for neotectonic activity in the Centennial

Valley/southern Madison Valley area suggests rapid ongoing uplift of the range (O'Neill et al., 1995); the presence of abundant poorly indurated and clay-rich rocks which are rapidly being eroded from the crest of the range by fluvial, colluvial, and mass-wasting processes supports this interpretation.

Based on the data from this study, scenarios for the tectonic evolution of southwestern Montana which include the modern basin-bounding faults as controlling deposition of the Renova Formation (e.g. Fields et al., 1985) can be ruled out unless the tectonic history of the Gravelly Range is discarded as anomalous with respect to the rest of the region.

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APPENDIX

XRF AND RADIOMETRIC ANALYSES OF BASALT FROM TEPEE MOUNTAIN

Run 1195, Ernest Jan Luikart, Montana State University

	LUI B1
Date	17-Dec-95
Unnormalized Results (Weight %):	
SiO2	48.91
Al2O3	16.99
TiO2	1.459
FeO*	8.50
MnO	0.159
CaO	9.22
MgO	8.99
K2O	1.49
Na2O	3.04
P2O5	0.383
Total	99.14
Normalized Results (Weight %):	
SiO2	49.33
Al2O3	17.14
TiO2	1.472
FeO*	8.57
MnO	0.160
CaO	9.30
MgO	9.07
K2O	1.50
Na2O	3.07
P2O5	0.386
Trace Elements (ppm):	
Ni	125
Cr	212
Sc	24
V	182
Ba	990
Rb	43
Sr	716
Zr	142
Y	26
Nb	†35
Ga	17
Cu	47
Zn	64
Pb	2
Th	3

Major elements are normalized on a volatile-free basis.
"R" denotes a duplicate bead made from the same rock powder.
*Total Fe is expressed as FeO.
"†" denotes values >120% of our highest standard.

WSU GeoAnalytical Laboratory *Analyses by XRF*

Report On $^{40}Ar/^{39}Ar$ Analysis for:

Ernest Luikart
Montana State University

Prepared by:

Lisa Peters
New Mexico Geochronological Research Laboratory (NMGRL)

Co-directors
Dr. Matthew Heizler
Dr. William C. McIntosh

Introduction

For the $^{40}Ar/^{39}Ar$ variant of the K-Ar technique, a sample is irradiated with fast neutrons thereby converting ^{39}K to ^{39}Ar through a (n,p) reaction. Following irradiation, the sample is either fused or incrementally heated and the gas analyzed in the same manner as in the conventional K-Ar procedure, with one exception, no argon spike need be added.

Some of the advantages of the $^{40}Ar/^{39}Ar$ method over the conventional K-Ar technique are:

1. A single analysis is conducted on one aliquot of sample thereby reducing the sample size and eliminating sample inhomogeneity.
2. Analytical error incurred in determining absolute abundances is reduced by measuring only isotopic ratios. This also eliminates the need to know the exact weight of the sample.
3. The addition of an argon spike is not necessary.
4. The sample does not need to be completely fused, but rather can be incrementally heated. The $^{40}Ar/^{39}Ar$ ratio (age) can be measured for each fraction of argon released and this allows for the generation of an age spectrum.

The age of a sample as determined with the $^{40}Ar/^{39}Ar$ method requires comparison of the measured $^{40}Ar/^{39}Ar$ ratio with that of a standard of known age. Also, several isotopes of other elements (Ca, K, Cl, Ar) produce argon during the irradiation procedure and must be corrected for. Far more in-depth details of the determination of an apparent age via the $^{40}Ar/^{39}Ar$ method are given in Dalrymple et al. (1981) and McDougall and Harrison (1988).

Analytical techniques

Whole rock sample Luikart-1 was crushed, sieved, treated with ~15% hydrochloric acid and hand picked to provide as clean a groundmass concentrate as possible. It was then placed in a machined Al disc and sealed in an evacuated Pyrex tube along with interlaboratory standard Fish Canyon Tuff (Age = 27.84 Ma). The standard was used to monitor the neutron dose received during the 7 hour irradiation in the D-3 position of the reactor at the Nuclear Science Center, College Station, TX. Following irradiation, monitors were placed in a copper planchet and analyzed in an ultra-high vacuum argon extraction system with a 10W Syrad CO_2 continuous laser. Evolved gases were purified for two minutes using a GP-50 SAES getter operated at ~450° C. The whole rock sample was step-heated in a double vacuum Mo resistance furnace. The samples were step-heated in a double vacuum Mo resistance furnace. The gas was gettered during heating for seven minutes with a SAES AP-10 getter, and additionally cleaned following heating with the GP-50 for an additional eight minutes. Argon isotopic compositions were determined with a MAP 215-50 mass spectrometer operated in multiplier mode with an overall sensitivity of 3.0×10^{-17} moles/pA . Extraction system and mass spectrometer blanks and backgrounds were measured numerous times throughout the course of the analyses and were very reproducible. Typical blanks (including mass spectrometer backgrounds) were; 2000, 1,1, 2, 8.9×10^{-18} moles at masses 40, 39, 38, 37, 36 respectively. J-factors were determined by using 4 separate, 4 crystal aliquots from 4 radial positions around the irradiation vessel. Correction for interfering nuclear reactions were determined using K-glass and CaF_2. These values are; $(^{40}Ar/^{39}Ar)_K = 0.00020 \pm 0.0002$, $(^{36}Ar/^{37}Ar)_{Ca} = 0.00026 \pm 0.00002$ and $(^{39}Ar/^{37}Ar)_{Ca} = 0.00070 \pm 0.00005$. All errors are reported at the two sigma confidence level and the decay constants and isotopic abundances are those suggested by Steiger and Jager (1977).

Results and Discussion

Luikart-1 32.38 ± 0.64 Ma

The preferred age for this sample is the isochron age (Figure 1) as it's $^{40}Ar/^{36}Ar_i$ of 300.2± 2.8 is higher than the atmospheric value of 295.5. The increasing radiogenic yield combined with decreasing ages, as seen on the age spectrum (Figure 2), is also indicative of excess argon.

Figure 1 Luikart 1 Whole Rock Isochron Steps D-O

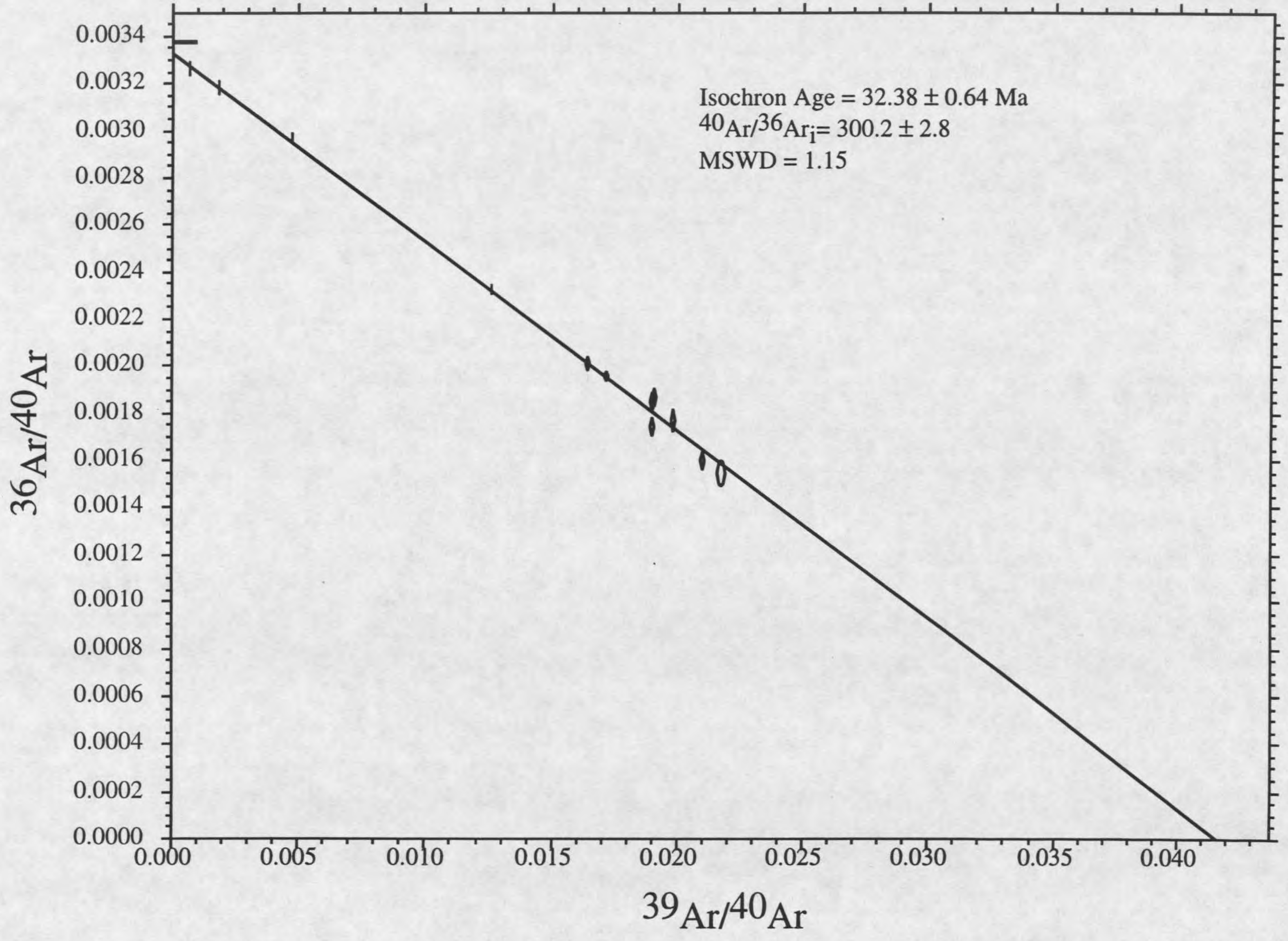

Figure 2 Luikart 1 Whole Rock Age Spectrum

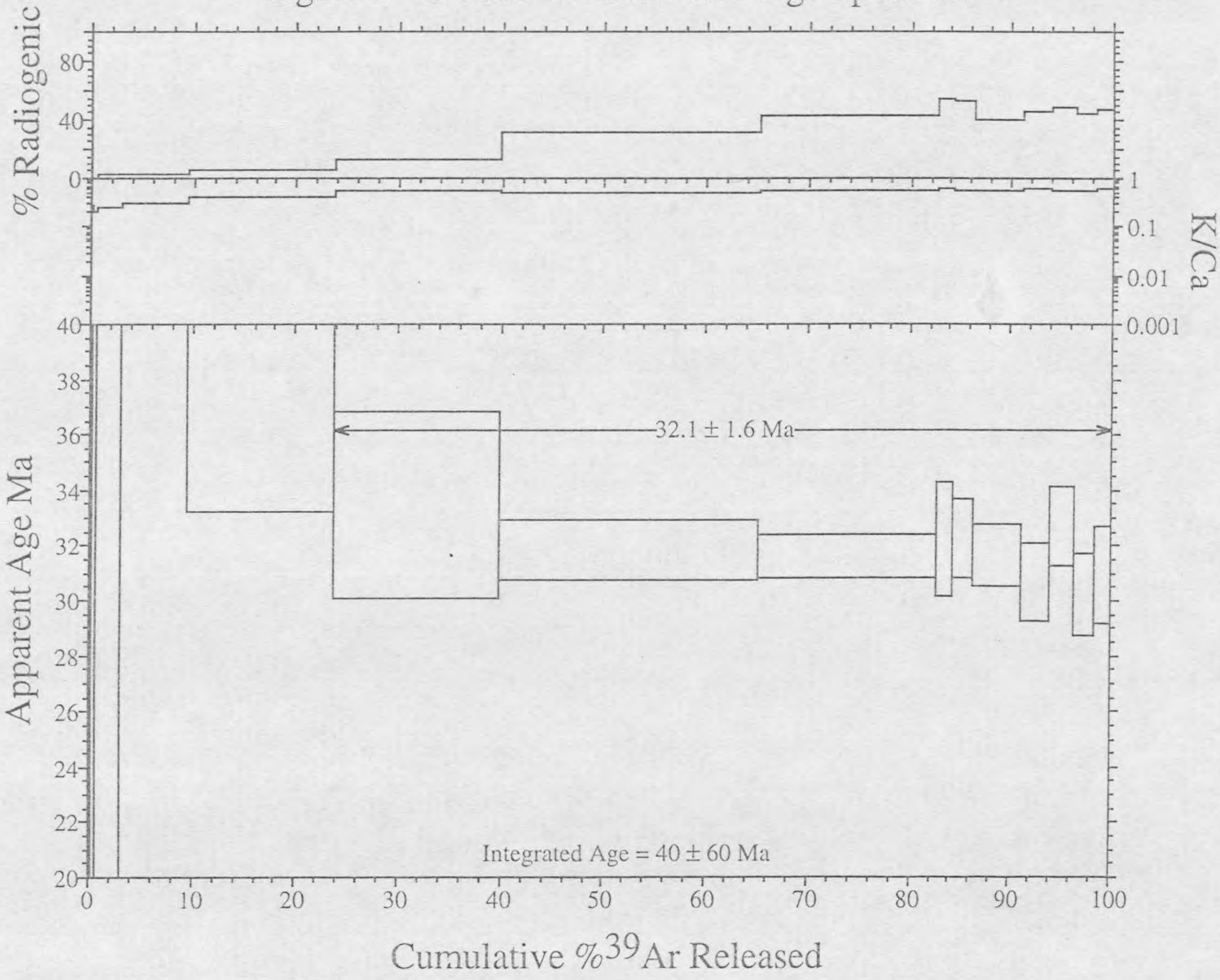

Table 1 Luikart-1 Data

Run ID#	Temp	$^{40}Ar/^{39}Ar_1$	$^{37}Ar/^{39}Ar_2$	$^{36}Ar/^{39}Ar_1$	$^{39}Ar_K$ mol ($X10^{-16}$)	K/Ca	$\%^{40}Ar_1$ rad	$\%^{39}Ar$ released	Age (Ma)	± 1 s.d. (Ma)
Luikart-1,19.82mg	**whole rock**		**J=0.0007545**							
6171-01C	750	3034	1.982	10.03	2.83	0.257	2.3	2.6	93	44
6171-01D	825	1595	1.597	5.205	7.06	0.320	3.6	8.9	76	16
6171-01E	900	558.5	1.194	1.777	16.0	0.427	6.0	23.4	45.2	5.2
6171-01F	975	210.9	0.9171	0.6260	17.7	0.556	12.3	39.5	35.0	1.8
6171-01G	1050	79.06	1.022	0.1841	28.3	0.499	31.3	65.0	33.37	0.57
6171-01H	1125	58.12	0.9058	0.1139	19.4	0.563	42.2	82.6	33.10	0.41
6171-01I	1200	45.99	0.8395	0.0712	1.84	0.608	54.4	84.3	33.7	1.1
6171-01J	1275	47.52	0.9046	0.0763	2.07	0.564	52.7	86.2	33.78	0.76
6171-01K	1350	60.68	0.9194	0.1225	5.48	0.555	40.5	91.1	33.15	0.58
6171-01L	1425	52.49	0.8435	0.0972	3.12	0.605	45.4	93.9	32.16	0.75
6171-01M	1500	52.48	0.9096	0.0918	2.72	0.561	48.4	96.4	34.29	0.75
6171-01N	1575	52.27	0.9324	0.0978	2.17	0.547	44.9	98.4	31.67	0.80
6171-01O	1650	50.47	0.8762	0.0898	1.80	0.582	47.5	100.0	32.39	0.92
		total gas age		n=13					39.5	3.6

$(^{39}Ar/^{37}Ar)_{Ca}$ = 0.00070±0.00005

$(^{36}Ar/^{37}Ar)_{Ca}$ = 0.00026±0.00002

$(^{40}Ar/^{39}Ar)_K$ = 0.0002±0.0003

1 Corrected for blank

2 Corrected for ^{37}Ar decay

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McDougall, I. and Harrison, T.M., 1988. Geochronology and thermochronology by the ^{40}Ar-^{39}Ar method. Oxford University Press.

Steiger, R.H. and Jager, E., 1977. Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology. Earth and Planet. Sci. Lett., 36: 359-362.

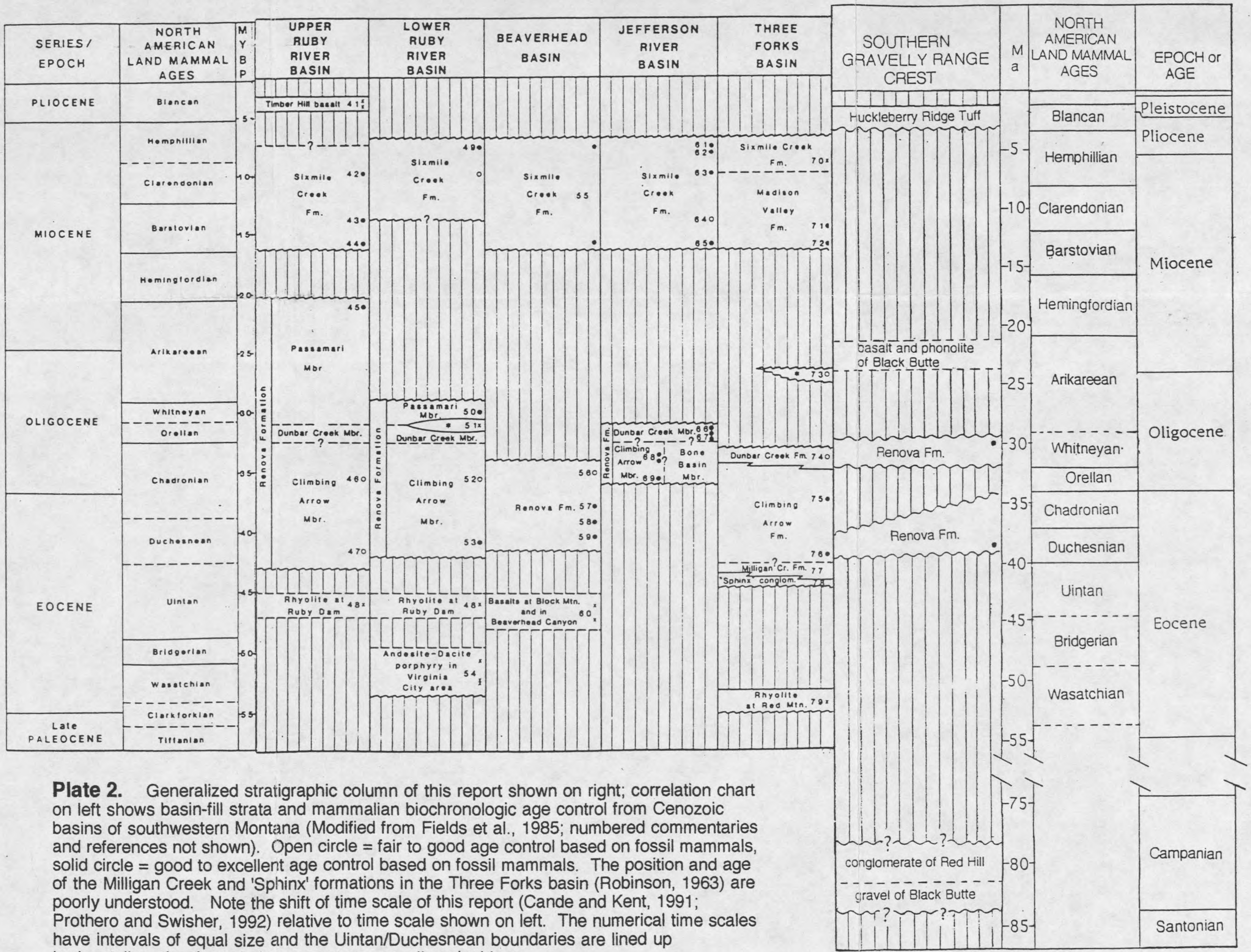
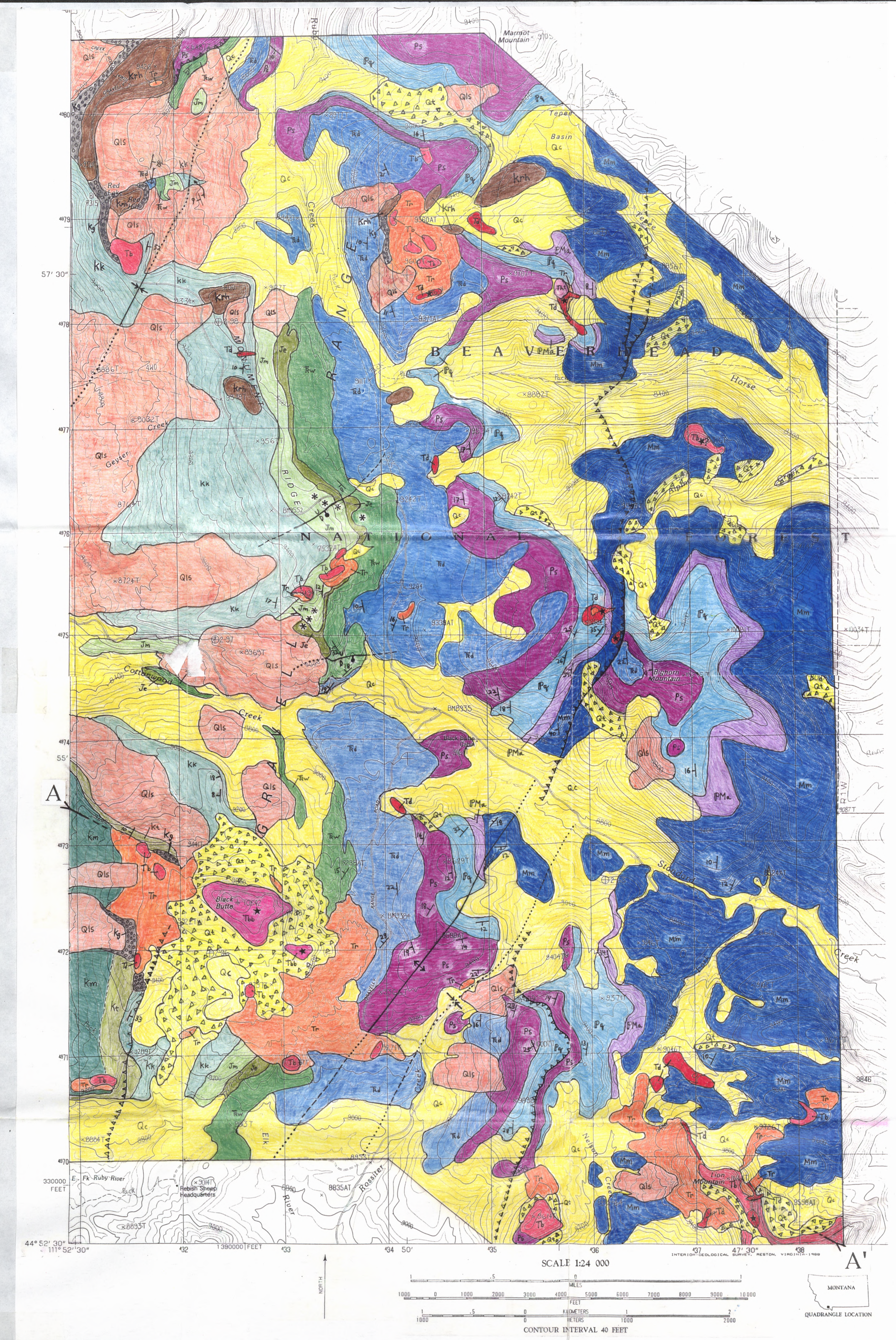
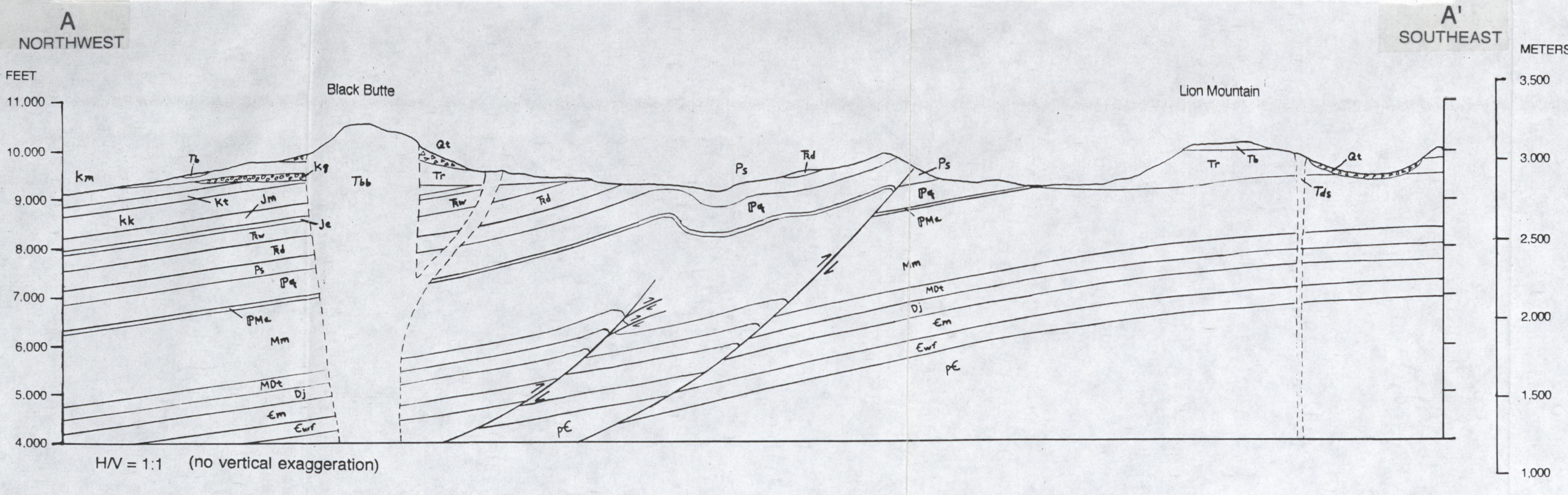


Plate 2. Generalized stratigraphic column of this report shown on right; correlation chart on left shows basin-fill strata and mammalian biochronologic age control from Cenozoic basins of southwestern Montana (Modified from Fields et al., 1985; numbered commentaries and references not shown). Open circle = fair to good age control based on fossil mammals, solid circle = good to excellent age control based on fossil mammals. The position and age of the Milligan Creek and 'Sphinx' formations in the Three Forks basin (Robinson, 1963) are poorly understood. Note the shift of time scale of this report (Cande and Kent, 1991; Prothero and Swisher, 1992) relative to time scale shown on left. The numerical time scales have intervals of equal size and the Uintan/Duchesnean boundaries are lined up horizontally; other boundaries are not necessarily coincident.

Plate 1. Geologic Map, South-Central Gravelly Range

Ernest Luikart, 1997





DESCRIPTION OF MAP UNITS

Qt **Talus (Holocene)**--- Unconsolidated deposits of angular blocks that accumulate at the base of cliffs or very steep slopes; includes basaltic rubble surrounding the Black Butte volcanic neck

Qls **Landslide deposits (Holocene)**--- Angular fragments of bedrock mixed with soil or heterogeneous mixtures of boulders and finer-grained material derived from adjacent hill slopes; characterized by hummocky topography and small ponded depressions. Also includes earthflows composed of clay rich, easily erodable Mesozoic and Tertiary rocks

Qc **Colluvial deposits (Holocene and Pleistocene)**--- Unconsolidated deposits of silt, sand, and angular pebbles, cobbles and boulders formed by downslope creep or surface wash; locally reworked as alluvium in stream drainages. Includes small remnants of unconsolidated Pleistocene glacial moraines in the lower parts of Standard Creek

Tht **Huckleberry Ridge Tuff (Pliocene)**--- Welded rhyolitic ash-flow tuff, consisting of a basal densely welded, dark-grey to black, glassy vitrophyre containing sanidine phenocrysts up to 3 mm, grading upward into a middle medium-grey unit which contains sanidine phenocrysts and is slightly less densely welded; the unit is capped by porous, light-greyish-pink welded tuff with a few small (1 mm) phenocrysts and numerous flattened pumice fragments. Total thickness for the tuff is about 1.5 m

Tbb **Basalt and Phonolite of Black Butte (Miocene)**--- Alkali basalt and diabase of the Black Butte volcanic neck, including pods and small dikes of tephritic phonolite near the top. Small outcrops of a thin, tan, mafic tuff overlying an eroded Renova mudstone blanket around the margins of Black Butte probably are an eruptive product; the tuff is not in place due to slumping and earthflow and is therefore not mapped (Gutmann et al., 1989). The diabase was given a whole-rock K-Ar date of 22.9 ± 1.2 Ma (Marvin et al., 1974). Outcrops of hydrothermal gypsum and chert, exposed in the Jurassic rocks northeast of the Butte, may have formed during cooling of the volcanic neck; they are denoted by asterisks

Tb **Basalt flows and associated vent facies (Oligocene)**--- Alkali basalt and scoriaceous agglomerate extruded from several vents within the field area. These basalts are included in the Renova Formation by McDowell et al. (1997, in press), but are mapped separately here. Where present, thickness varies from 1 to 30 m. ★ – indicates scoriaceous vent agglomerate. Two radiometric analyses have been done on flows in the map area; a whole-rock $^{40}Ar/^{39}Ar$ date of 32.38 ± 0.64 Ma on a flow capping Tepee Mountain (see appendix), and a whole-rock K-Ar date of 30.38 ± 0.7 Ma (Gutmann et al., 1989) on a flow at the top of Lion Mountain

Td **Mafic dikes (Oligocene)**--- Near-surface intrusive alkali basalt and diabase, usually associated with local basaltic vents and basalt flows. May be included as part of the Renova Formation (as noted above), but mapped separately here

Tr **Renova Formation (Oligocene and Eocene)**--- Pale cream-colored to light-tan tuffaceous montmorillonitic mudstone containing mammal fossils and locally abundant carbonate concretions. Numerous small (3 mm) fossilized earthworm casts are found in some outcrops. The mudstones are poorly indurated and massive, showing little or no sign of bedding except near the top of Lion Mountain, where thin granule-pebble conglomerate interbeds contain clasts of Paleozoic limestone and Tertiary basalt. Thickness ranges from 0 to as much as 240 m

Krh **Conglomerate of Red Hill (Late Cretaceous)**--- Dominantly large lenticular bodies of clast-supported, limestone pebble to boulder conglomerate in a red to orange argillaceous, partly calcareous silt and sand matrix. In the Red Hill/Lazyman Hill area, the conglomerate is interbedded with white to reddish lacustrine limestone, red siltstone and coarse yellowish-brown litharenite sandstone containing abundant schist and phyllite fragments. The lacustrine limestone locally contains fossil freshwater snails, oncolites, stromatolites and vertebrate bones. A deposit of angular breccia of Shedhorn Sandstone clasts in a calcareous red matrix is included as a locally derived lithosome at Tepee Mountain. Thickness ranges from 0-40 m

Kg **Gravel of Black Butte (Lower Cretaceous)**--- Unconsolidated gravel of extremely well-rounded quartzite pebbles and cobbles with moderately-rounded Archean metamorphic cobbles and boulders locally dominating the clast composition. Minor Paleozoic limestone clasts and rare angular boulders of Shedhorn Sandstone are present. The matrix of the gravel consists of a coarse, angular, white- to yellowish-orange-stained quartz sand with some silt. Thickness ranges from 0-10 m; the unit is present only along the western margin of the map area

Km **Muddy Formation (Lower Cretaceous)**--- Grey to dark-brown, medium-grained, calcareous argillaceous sandstone, thin- to medium-bedded, containing carbonized plant remains; about 40 m thick

Kt **Thermopolis Shale (Lower Cretaceous)**--- Basal sandstone of the Thermopolis is a quartzitic sandstone with thin shale interbeds; upper part is medium-grey to black fissile shale, containing brown-weathering concretions and thin sandstone interbeds. Total thickness is about 30-40 m

Kk **Kootenai Formation (Lower Cretaceous)**--- Lower part consists of grey to light-brown, commonly cross-stratified sandstone, with numerous pebbly layers and a chert-pebble conglomerate at the base; middle part is silty, light-tan to light-grey, poorly lithified mudstone and sandy siltstone, poorly exposed; upper part contains a dark-grey limestone consisting of small gastropod shells in a micritic matrix. Total thickness is about 120 m

Jm **Morrison Formation (Upper Jurassic)**--- Generally poorly-exposed maroon, pinkish-grey , green, and light-grey medium-bedded mudstone and siltstone, with some discontiuous thin sandstone beds. A limb-bone of a dinosaur (sauropod) was recovered in mudstone at the south end of Monument Ridge. Thickness is about 45-50 m

Je **Ellis Group, undivided (Upper and Middle Jurassic)**-- Medium- to coarse-grained sandstone with rounded chert-pebble conglomerate at the base; some grey limestone and light brown to tan siltstone in the upper part. Thickness varies from 10-15 m

TRw **Woodside Formation (Lower Triassic)**--- Thin- to medium-bedded red siltstone, sandstone, and shale; thickness is 70-90 m, but the unit pinches out rapidly northward of the map area

TRd **Dinwoody Formation (Lower Triassic)**--- Thin-bedded yellow to light-brown siltstone interbedded with yellowish- to pinkish-grey dolomite. *Lingula* fossils locally abundant on bedding surfaces. About 120-125 m thick

Ps **Shedhorn Sandstone (Lower Permian)**--- Light-grey, fine- to medium-grained, brown-weathering quartzitic sandstone which contains white and black chert grains; medium- to thin-bedded, often cemented and partly replaced with chert. Large (5 cm-wide) burrow structures filled with yellowish- to reddish-brown chert locally abundant in the upper part. Thickness is 60-65 m

IPq **Quadrant Formation (Pennsylvanian)**--- Fine- to medium-grained, well-sorted, white to pale-grey quartz sandstone; bedding usually indistinct but locally cross-stratified; mostly calcite-cemented, but quartz-cemented in some outcrops. Beds of 1 to 3 m-thick dolomite occur in the middle and lower part. Thickness ranges from 120 to 150 m

IPMa **Amsden Formation (Lower Pennsylvanian and Upper Mississippian)**--- 1 to 4 m-thick blue-grey fossiliferous limestone beds with red argillaceous sandy siltstone and shale in the middle part. Basal unit consists of fissile yellow to tan shale and fine sandstone. Total thickness varies from 15 to 40 m

Mm **Madison Group, undivided (Upper and Lower Mississippian)**--- Olive-grey , light-grey-weathering, medium- to thick-bedded, micritic to medium-grained limestone; locally fossiliferous, especially in middle and lower parts. Large karsts filled with solution breccia and siltstone found locally near the top, associated with fault zones. Thickness ranges from about 470 to 600 m (Hadley, 1960; Mann, 1960)

Map units below not exposed in field area. Stratigraphy based on Hadley (1960) and Mann (1960)

MDt **Three Forks Formation (Mississipian and Upper Devonian)**--- Dolomite and limestone breccia in a red argillaceous matrix at base; thick-bedded grey fine-grained limestone and grey to black shale in middle part; yellowish-orange calcareous sandstone and sandy siltstone in upper part. Thickness ranges from 60-75 m

Dj **Jefferson Dolomite (Upper and Middle Devonian)**--- Dolomite, moderate- to dark-yellowish-brown to dark-grey, thick- to medium-bedded, vuggy and petroliferous. Thickness is about 90 m

Єm **Meagher Limestone (Upper and Middle Cambrian)**--- Mottled light- to medium-yellowish-brown dolomite and limestone, thin- to thick-bedded, locally weakly petroliferous. Reported thickness ranges from about 300 m (Mann, 1960) to 110-120 m (Hadley, 1960)

Єwf **Wolsey Shale and Flathead Sandstone, undivided (Middle Cambrian)**--- Light-brown to reddish-brown or white quartzitic sandstone with thin interbeds of greenish-gray shale, overlain by green fissile shale and sandy shale with thin interbeds of glauconitic sandstone. Thickness is about 60 to 100 m

pЄu **Precambrian rocks, undivided (Proterozoic(?) and Archean)**--- Quartzofeldspathic gneiss, amphibolite, schist, quartzite, mafic intrusives, and iron-formation

(Contacts, faults, anticlines, and synclines are shown by solid lines where accurately located, dashed lines where approximately located, dotted lines where concealed)

Contact

High-angle fault- ball and bar on downthrown side

Thrust fault- sawteeth on upper plate

Anticline

Syncline

Strike and dip of beds