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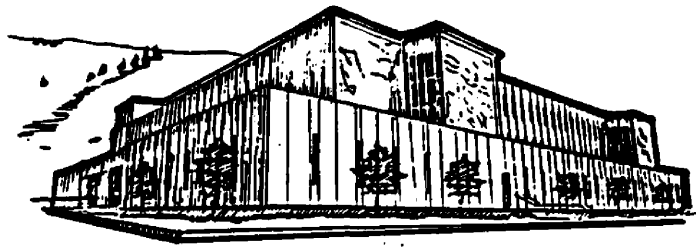
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University of  
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**THE GEOLOGY AND GEOMORPHOLOGY OF LOBO MESA:  
EVIDENCE OF MIDDLE MIOCENE VOLCANISM AND QUATERNARY  
TECTONISM IN THE GRAVELLY RANGE, MONTANA**

**By**

**Monte P. Smith**


**B.S., Montana State University, 1988**

**Presented in partial fulfillment of the requirements  
for the degree of  
Master of Science  
University of Montana  
1992**

**Approved by**

  
Chairman, Board of Examiners

  
Dean, Graduate School

  
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ABSTRACT

Smith, Monte P., M.S., December 1992

Geology

The Geology and Geomorphology of Lobo Mesa: Evidence of Middle Miocene Volcanism and Quaternary Tectonism in the Gravelly Range, Montana (46 pp.)

Chairman: Jim Sears

YAS

Lobo Mesa is a previously unrecognized basalt eruptive center on the southern flank of the Gravelly Range in SW Montana. At least five sheets of alkali basalt erupted from a northwest-trending dike and vent system on the northwest margin of the mesa. The basalt covers a bedrock erosional surface consisting of Paleozoic strata and Archean metamorphic rocks. Volcanism created about 180 meters of relief on the bedrock erosional surface establishing the radial drainage pattern of the six streams that originate on the mesa. Major element geochemistry shows that the flows are distinct from other basalt of the region. A middle Miocene K-Ar whole rock date of 16.9 +/- 0.3 Ma on one of the flows places Lobo Mesa as the youngest known basalt eruptive center in the Gravelly Range.

Following the birth of the Yellowstone Plateau volcanic field at the Pliocene/Pleistocene boundary, west-trending, down-to-the-south normal faults formed on Lobo Mesa. The mesa was down-faulted and tilted to the south as part of a rollover anticline that formed in response to listric normal offset on the Yellowstone Plateau-related Centennial fault. Smaller scale landforms, including sinkholes and landslides, that appear to be related to Quaternary extension exist along the northern margin of the mesa.

## ACKNOWLEDGMENTS

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I thank W.J. Fritz and J.M. Wampler for providing a K-Ar date for the basalt sample, and Bud Warmouth for performing Au/Ag assays at 'student' rates.

Amoco Oil Company provided generous financial support to this project when I needed it most. Mike Stickney openly shared his time, and knowledge of southwestern Montana. To both I offer my gratitude.

Special thanks go to my sister, Marianne, and brothers, Marc and Lynn, for their logistical support in the field. Also, to my parents, Eldon and Lois, for making sure I was born in Montana.

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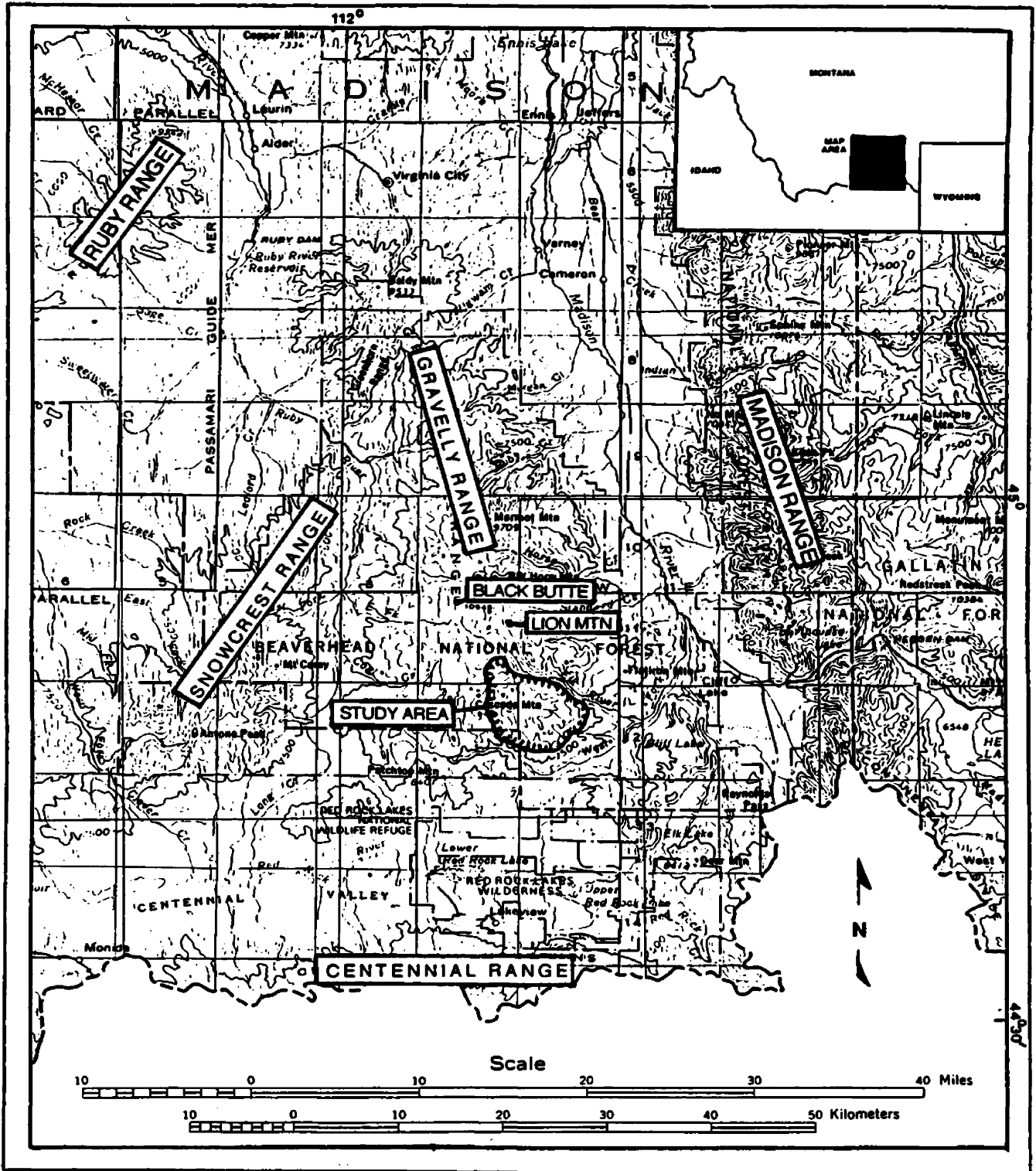


Figure 1. General location of study area. Map modified from U.S. Geological Survey 1:500,000 topographic map of Montana.

## **(1) INTRODUCTION**

### **(1.1) General**

The Gravelly Range is located in the central part of the Rocky Mountain foreland of southwestern Montana. Contained within the range is an impressive variety of rocks and features that record a rich geological history. Precambrian tectonism is recorded in the basement rocks. Thrust faults and gentle folds in the Phanerozoic rocks are evidence of late Cretaceous deformation during the development of the Montana thrust belt. And although little evidence of Quaternary deformation has been recognized in the Gravelly Range, Fritz and others (1989) and Stickney and Bartholomew (1987) believe that Yellowstone hotspot tectonism has profoundly influenced landforms during Quaternary time. The stratigraphy embraces a nearly complete section from Precambrian to Quaternary rocks and sediments. Missing, as in most of North America, are rocks of early Cambrian, Ordovician, Silurian and early Devonian age. Radiometric dates show that the range has been a center for intermittent basaltic volcanism, and part of a regional depositional basin, since Eocene time.

### **(1.2) Objective of the Study**

The objective of this project is to complete a detailed field study of the geological development of Lobo Mesa; generally to add to the body of knowledge of southwestern

Montana; more specifically to evaluate the late Cenozoic history of the Gravelly Range.

Lobo Mesa is the focal point because it is a distinct geomorphic element of the southern Gravelly Range, it exhibits good structural and rock diversity, and it has never been mapped in detail. Structures on the mesa provide evidence of Quaternary tectonism as well as events dating back to Proterozoic time. Rock units consist of Tertiary basalt and rhyolite tuff underlain by Paleozoic and Precambrian rocks.

### (1.3) Location and Access

Lobo Mesa lies on the southeastern flank of the Gravelly Range in southwestern Montana between 111.67-111.83 west longitude and 44.75-44.83 north latitude (Figure 1). The study area includes about 60 square kilometers along the border between Beaverhead and Madison counties, and is within the Beaverhead National Forest. The U.S. Geological Survey Windy Hill and Freezeout Mountain 7.5 minute quadrangles provide topographic map coverage.

Access to Lobo Mesa is by trail. From the west, the trailhead is on the Gravelly Range Road about 2.5 km north of the West Fork Ranger Station. From the southeast, the trail begins at the Partridge Cow Camp on the West Fork of the Madison River. Both routes are about 9 km long. The trails are open yearlong to pedestrians, equestrians and vehicles under 40 inches in width.

#### (1.4) Previous Work

Earlier geologic investigations of Lobo Mesa have been parts of studies focused more on the central part of the Gravelly Range.

A reconnaissance map of the Gravelly Range is presented by Conduit and others (1927) in their report on phosphate rocks in southwestern Montana. They also describe two measured sections of the Phosphoria and Quadrant formations.

Lemish (1948) and Christie (1961) mapped the geology of the West Fork of the Madison River, an area that includes the eastern and southeastern margins of Lobo Mesa. Both provide descriptions of the Precambrian rocks and a measured section of the Paleozoic to Late Cretaceous age rocks.

A geologic map of the central Gravelly Range, which includes the northern-most portion of Lobo Mesa, was completed by Mann (1954). His study also offers detailed rock descriptions, measured sections, a composite stratigraphy of Precambrian to Quaternary rocks and sediments, and a structural interpretation of the area. Geologic maps completed by Hadley (1969) show the geology of the northern Gravelly Range.

The Tertiary history of the Gravelly Range has been studied by Scott (1938), Atwood and Atwood (1945), Priore (1984) and Gutmann and others (1989). Each report emphasizes the source or depositional history of the gravel deposits along the crest of the range.

Spaid-Reitz (1980) presents geochemical and isotopic data of the Tertiary volcanic rocks, including those capping Lobo Mesa, in her examination of the basalt lava and rhyolite tuff in the Gravelly Range. Burke-Griffin (1978) presents petrographic and geochemical data for the Black Butte volcanic neck. Eichen (1979) studied the Tertiary volcanic rocks in Wolverine Basin to the north of Lobo Mesa, and Marvin and others (1974) and Daniel and Berg (1981) present radiometric dates of Tertiary volcanic rocks within and surrounding the Gravelly Range.

Millholland (1976) and Erslev (1983) provide mineralogical descriptions of the Precambrian, Cherry Creek metamorphic suite of rocks that occur along the eastern flank of the Gravelly Range.

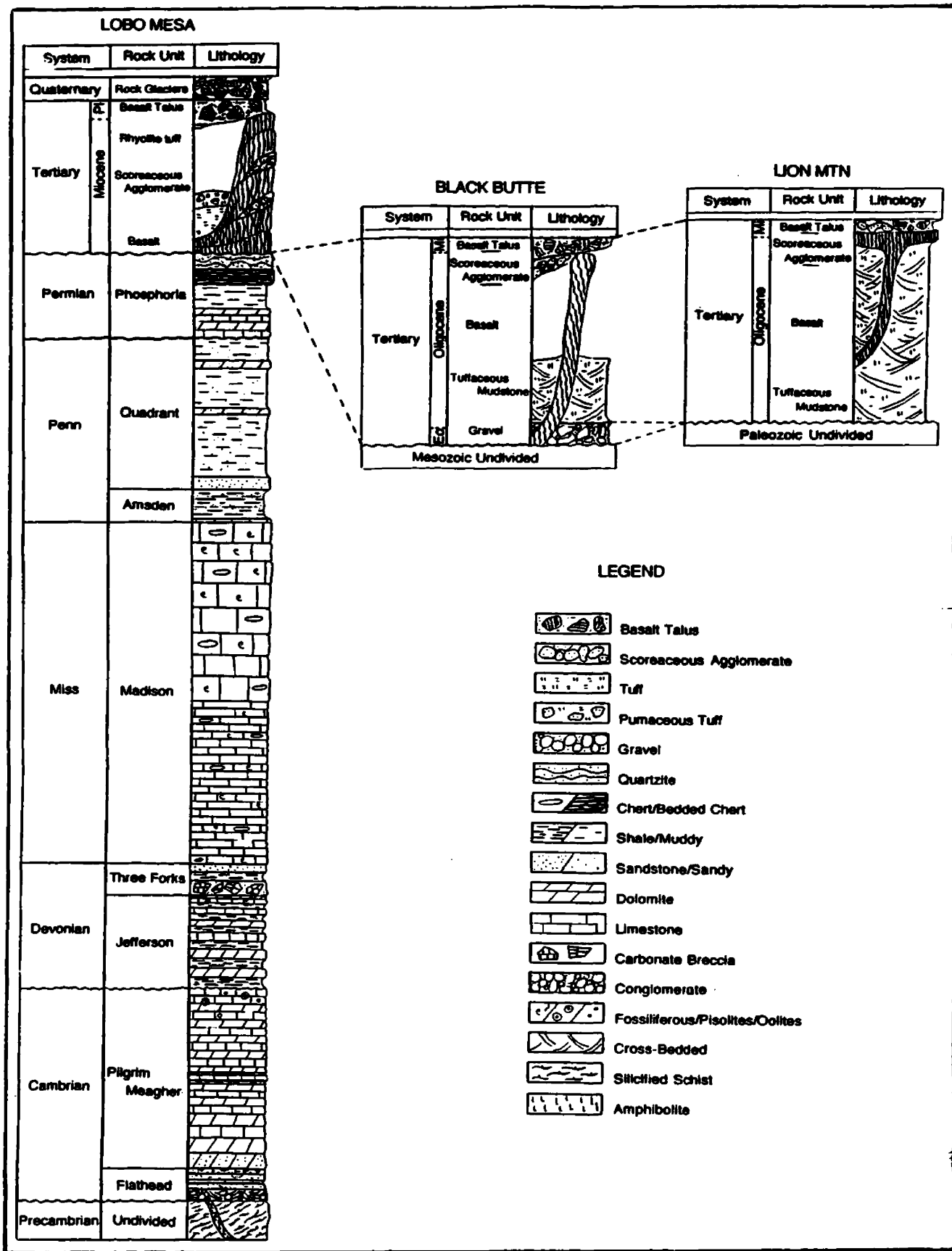


Figure 2. The stratigraphy of Lobo Mesa, and late Cenozoic stratigraphy of Black Butte and Lion Mountain.



## (2) STRATIGRAPHY

### (2.1) General

About 1,000 meters of Paleozoic rocks are exposed on Lobo Mesa (figure 2). Burial of these rocks by Tertiary lava flows, thick talus slopes and heavy timber cover on lower slopes make detailed section measurements impractical. Estimates of unit thickness presented in this thesis are based on map data (back pocket). Detailed section measurements of Paleozoic rocks in the Gravelly Range are presented in studies by Conduit and others (1927), Mann (1954), Lemish (1948) and Christie (1961).

### (2.2) Precambrian System (pCu)

Basement rocks flanking the eastern margin of Lobo Mesa include biotite-actinolite schist and amphibolite.

Schist at the southern portion of the study area, near Tepee Creek, is light greenish-tan to black, depending on the abundance of biotite. The rock is composed of 5 to 10 percent quartz porphyroblasts 3 to 5 millimeters in diameter that take on a purple hue in biotite-rich rocks, and less than 1 % euhedral orthoclase porphyroblasts 2 to 3 mm in diameter. The matrix is fine-grained and strongly silicified. Cross-cutting quartz veins and veinlets, subparallel to schistosity, become more abundant approaching the southern-most normal fault, and abruptly grade into a silica matrix surrounding brecciated Precambrian rocks along the trace of the fault.

Petrographic analysis reveals a shistose texture and a rock composition of about 50 to 60 % quartz, 20 to 30 % actinolite, 1 to 10 % biotite and less than 1 % orthoclase. Accessory minerals include sphene, epidote and opaque minerals altered to leucoxene.

Amphibolite north of Dirty Creek is a greenish-black, massive, medium-grained rock that distinctly lacks the shistosity of the host rock. Petrographic analysis shows a massive, subhedral texture with bent hornblende crystals, and a rock composition of about 70 % hornblende, 15 % chlorite, 10 % quartz, 2 % plagioclase, 2 % opaque minerals and less than 1 % apatite. Quartz veinlets are rare.

Erslev (1983) classifies the Precambrian rocks as members of the Cherry Creek metamorphic suite. He believes mineral assemblages suggesting a calcareous protolith and the relative scarcity of isoclinal folding distinguishes the Cherry Creek metamorphic suite from rocks of the Precambrian Pony series.

### (2.3) Cambrian System

#### (2.3.1) Flathead Formation (Cf)

The unconformable contact between Precambrian rocks and the overlying Flathead Formation appears at the southern-most normal fault near the upper reach of Tepee Creek. The basal Flathead Formation crops out as a clast-supported, imbricated, cross-bedded pebble-cobble conglomerate containing subrounded clasts composed of the underlying, porphyroblastic,

Precambrian schist. The matrix consists of medium to coarse-grained, subangular, moderately silicified sand. Faulting has disturbed much of this outcrop, making the imbricated clasts unlikely candidates for accurate paleocurrent indicators.

Upper units of the Flathead Formation are best exposed along the Elk River in the northern part of the study area. They consist of a red, glauconitic, crossbedded, fine to coarse-grained, subrounded, quartz-feldspar-rock fragment sandstone with bedding thinning upward from about 30 centimeters to 3 cm thick. This is overlain by a light yellow, medium grained, glauconitic, quartzitic sandstone with bedding thinning upward from about 30 cm to 3 cm thick. Symmetric ripple marks appear on bedding planes of both units. Total unit thickness is approximately 30 meters.

The Wolsey Formation, commonly found overlying the Flathead Formation in southwestern Montana, has been mapped in the Gravelly Range by Mann (1954), Christie (1961) and Lemish (1948). They describe it as a fissile, swale-forming, green shale. Within the study area, the only evidence of the Wolsey shale is a thin, green siltstone interbedded with the red and light yellow sandstone near the top of the Flathead Formation. In this study the interval is included with the Flathead Formation.

Depositional models presented by Davis (1983), Miall (1985) and Fritz and Moore (1988) suggest the Flathead Formation is a marine transgressive sequence; the basal conglomerate showing evidence of fluvial deposition; the upper sandstone having characteristics more common to shoreline sediments.

#### (2.3.2) Meagher-Pilgrim Formation (CMu)

The Meagher-Pilgrim Formation is approximately 180 m thick and crops out as steep cliffs above the Little Elk River. This formation conformably overlies the Flathead Formation on a contact that grades upward from quartzitic sandstone to sandy dolomite.

Rock types and outcrop characteristics divide this section into two units. The lower unit consists of subtly gray-brown mottled, interbedded, sparry dolomite and micritic limestone. Bedding thins upward from about 1.5 m to 30 cm thick. The upper unit has an easily distinguishable gray-brown mottling and a consistent bedding thickness of about 10 centimeters. Angular pebble, matrix supported conglomerates appear at the base, and very distinct light gray- yellow mottling appears in the uppermost limestone beds of the upper unit. Separating the upper and lower units is a limestone bed about 40 cm thick, bound on the top and bottom by about 10 cm of fissil, light yellow siltstone. A moderate petroliferous odor pervades the entire section. Pisolites and oolites were not

observed in outcrop but occasionally found in the float that forms thick talus slopes at the base of the section. They are commonly contained in light gray limestone suggesting they came from the upper unit. Normal faulting within this section produced calcite cemented carbonate breccias.

Mann (1954) and Christie (1961) present lithologic and physical descriptions of this section north and south of Lobo Mesa respectively. To judge from its stratigraphic position and rock types the lower unit appears to correspond with the Meagher Formation; the upper with the Pilgrim Formation. The thin limestone-siltstone layer separating the section may be an expression of the Park Formation that crops out intermittently across the Gravelly Range.

Overlying the Cambrian limestone and dolomite is a shale unit about 2 m thick that forms a dark brown soil. In this study the interval is mapped with the Meagher-Pilgrim Formation but it may correspond with the Dry Creek shale. Mann (1954) states that the Dry Creek shale is absent in the central Gravelly Range. Lemish (1948) mapped a section of Dry Creek shale along the West Fork of the Madison River and describes it as friable with a variegated red-orange-pink color.

## (2.4) Devonian System

### (2.4.1) Jefferson Formation (Dj)

Unconformably overlying the Meagher-Pilgrim Formation are the interbedded shale-dolomite-limestone rocks of the Jefferson Formation. Within the study area, the Jefferson Formation forms a stepped topography with limestone-dolomite ledges and shale slopes. It is about 100 m thick and crops out along Hell Roaring Creek, Portal Creek, Lobo Creek and south of the Little Elk River. Basal units are dark brown, sparry dolomite with a strong petroliferous odor and 30 cm to 60 cm thick beds that crop out intermittently between shale units. Medium gray limestone beds thinning upward from approximately 30 cm to 3 cm appear between the shale-dolomite layers near the middle of the section and continue to the top. Stromatoperoids exist locally within the upper limestone rocks. Trace fossils of worm burrows and concentrically laminated spheres about 3 cm in diameter abound in the upper dolomite layers. Dolomitization has destroyed much of the internal structure of the laminated spheres, but their resistance to weathering gives weathered outcrops a distinct lumpy appearance.

Dorobek and Smith (1989) believe the Jefferson Formation in southwestern Montana represents cyclic shallow marine sedimentation on a tectonically active platform. Pervasive dolomitization of the Jefferson Formation probably

occurred during deposition of evaporite units in the overlying Three Forks Formation.

#### (2.4.2) Three Forks Formation (Dt)

Overlying the Jefferson Formation with apparent conformity, the Three Forks Formation is estimated at 27 m thick. It consists of carbonate breccia, shale and sandstone. The best exposures of this section are along Hell Roaring Creek and Cascade Creek. The basal unit is a massive, red-yellow-tan mottled or brown, thick-bedded breccia with limestone and dolomite clasts in a sandy, calcareous matrix. Nonresistant, yellowish-tan siltstone and fine grained sandstone appear as float on slopes overlying the brecciated unit. Found low on the talus slopes composed of Madison Group limestone that bury much of the Three Forks Formation in the study area are concentrations of pumpkin orange, fine grained, weakly calcareous, quartz sandstone. They may represent the upper unit of the Three Forks Formation.

Lithologically equivalent units of the Three Forks Formation have been mapped by Mann (1954) in the Gravelly Range and Tysdal (1976) in the Ruby Range. Tysdal (1976) believes the basal unit is a dolomite and limestone evaporite solution breccia.

## **(2.5) Mississippian System**

### **(2.5.1) Madison Group (Mm)**

Inspiring cliffs of the Madison Group carbonate rocks tower above Hell Roaring Creek and Cascade Creek, exposing a section estimated at 350 m thick.

The Madison Group consists of the lower Lodgepole Formation and upper Mission Canyon Formation. The Lodgepole Formation is a medium brown, fossiliferous, micritic limestone with uniformly thin beds, about 10 cm thick. Brown chert nodules, and thin interbeds of light gray limestone composed of more than 90 % fossil fragments were observed near the basal part of the unit. Limestone of the overlying Mission Canyon Formation is light gray, cherty, massively bedded and fossiliferous with an abundance of crinoid stems, brachiopods and horn corals distributed throughout. Changes in color and bedding thickness between the two formations are visible at a distance on cliff faces.

Tysdal (1976), Sando and others (1985), and Vice and Utgaard (1989) believe that the Madison Group was deposited mainly on a shallow marine shelf with subordinate components of deep water fore-reef deposition indicated by ribbon chert deposits.

## **(2.6) Pennsylvanian System**

### **(2.6.1) Amsden Formation (lPa)**

Although not well exposed, the estimated 35 m thick Amsden Formation is clearly marked along the western margin of Lobo



Mesa by the bright red soil that covers the rock. Float consists of red, fissil shale and siltstone and weakly calcareous, fine grained, quartz sandstone. Basal units of the Amsden Formation, exposed above the steep cliffs formed by the Madison Group rocks west of Cascade Creek, consist of light gray limestone beds, approximately 60 cm thick, that appear to be interbedded with red shale.

Mann (1954) observed lenses of brecciated limestone at the Amsden Formation-Madison Group contact in the central Gravelly Range, suggesting a considerable period of erosion before deposition of Amsden sediments. Wardlaw (1989) observed that the Amsden Formation becomes younger to the east in southwestern Montana suggesting to him that the sand came from the northwest. He believes that Amsden sediments filled a shelfal trough, then spread to relatively higher areas.

#### (2.6.2) Quadrant Formation (1Pq)

Overlying the Amsden Formation with apparent conformity, the approximately 150 m thick Quadrant Formation appears within the study area as gentle, grass covered slopes that provide only hints to the intraformational stratigraphy. Soil covering the Quadrant Formation is generally light tannish-yellow, in sharp contrast with the red soil blanketing the Amsden Formation. Float at the base of the section consists mainly of light tan, fine grained, porous, well sorted, quartz sandstone with well rounded grains. Upsection, float contains

a mixture of tan to yellow dolomite or sandy dolomite and fine grained, porous, quartz sandstone colored white, yellow, or tan. Although no sedimentary structures were observed in float within the study area, Mann (1954) observed cross beds in outcrops of Quadrant quartz sandstone in the central Gravelly Range. Thick talus composed of overlying Permian rocks cover the upper portion of the Quadrant Formation.

Davis (1983) and Miall (1985) present depositional models that suggest the Quadrant Formation may be the combined result of shallow marine and aeolean depositional environments.

## (2.7) Permian System

### (2.7.1) Phosphoria Formation (Pp)

A distinct ridge at the northwestern boundary of the study area is the upper quartzite and chert units of the approximately 150 m thick Phosphoria Formation. The top of the formation consists of white to medium brown, medium grained quartzite. Underlying the quartzite are horizontally continuous layers of brown chert in beds that thin downward from about 15 cm to 3 centimeters. What appear to be trace fossil worm burrows filled with fine sand exist locally in the chert.

Talus slopes cover much of the outcrop below the bedded chert. However, in the central Gravelly Range, Mann (1954) located complete sections of the formation and states that the chert is underlain by beds of phosphatic shale and oolitic

phosphate rock, in turn underlain by thin bedded dolomites, limestones and sandstones. He believes the Phosphoria-Quadrant contact to be unconformable.

The depositional history of the Phosphoria Formation, especially the phosphatic shale, oolitic phosphate rock and bedded chert remains unclear. Guilbert and Park (1985) state that the process of phosphate precipitation appears to involve upwelling of deep, cold seawater and its longshore flow across shallow, warm, sunlit shelf environments. Mansfield (1931) suggests a source of silica for the chert beds may be from volcanic tuffs.

## (2.8) Tertiary System

### (2.8.1) Basalt (Tb) and Basalt Dikes (Td)

Burying much of the Paleozoic section on Lobo Mesa are at least 5 flow units of basaltic rocks measuring up to 180 m thick. This study shows that the basalt erupted from a previously unrecognized dike and vent system oriented west-northwest along the northwestern flank of the mesa. A middle Miocene whole rock K-Ar date of  $16.9 \pm 0.3$  Ma (Fritz, personal communication, 1992) from sample location 1 (see map, back pocket) on one of the flows places Lobo Mesa as the youngest volcanic field currently known in the Gravelly Range. Springs flow from beneath the basalt, at the contact with Paleozoic rocks.

Outcrops of the basalt show crude columnar jointing. Different flows are distinguished by vesiculated zones within about 1 m of the top, and occasionally scoriaceous agglomerates between flow layers. The basalt is porphyritic with millimeter-scale phenocrysts of olivine and pyroxene, vesicular with local amygdaloidal calcite, weakly magnetic and colored maroon or purple on weathered surfaces. Petrographic analysis reveals a hypocrySTALLINE, inequigranular, vesicular texture. The ground mass is about 60 % plagioclase (An 50-70), 10 % opaque minerals and 5 % glass, the phenocrysts are 10 % olivine and 5 % combined orthopyroxene and clinopyroxene. Accessory minerals include iddingsite as an alteration product after olivine, calcite in veinlets and filling vesicles, and disseminated chlorite.

Spaid-Reitz (1980) classifies the rock as a silicic-alkali basalt, and presents geochemical data comparing the major element content and CIPW normative mineral composition of Lobo Mesa basalt with Lion Mountain and Black Butte basalt (table 1).

---

OXIDES (wt%)	LOBO MESA	BLACK BUTTE	LION MTN
SiO <sub>2</sub>	49.54	48.20	51.40
Al <sub>2</sub> O <sub>3</sub>	14.90	16.33	13.91
Fe <sub>2</sub> O <sub>3</sub>	9.31	10.25	8.94
MgO	4.39	4.05	7.69
CaO	10.68	9.71	7.61
Na <sub>2</sub> O	2.95	3.31	3.23
K <sub>2</sub> O	1.64	2.52	1.80
IGNITION	3.83	2.23	1.42
H <sub>2</sub> O	0.83	0.72	0.90
TiO <sub>2</sub>	1.40	2.65	1.79
MnO	0.16	0.14	0.11
TOTAL	99.63	100.07	98.80
NORMATIVE MINERALS (wt%)			
Q	0	0	0
C	0	0	0
OR	9.68	13.16	12.93
AB	24.94	20.50	27.48
AN	22.55	22.78	16.89
NE	0	4.38	0
DI	25.16	21.06	16.88
HY	2.41	0	7.29
OL	5.49	8.21	10.03
MT	1.71	1.99	1.66
IL	2.66	5.04	3.40

---

Table 1. Major element geochemistry and CIPW normative minerals for Lobo Mesa, Black Butte and Lion Mountain Basalt from Spaid-Reitz (1980).

### (2.8.2) Rhyolite Tuff (Tr)

Scattered across the top of Lobo Mesa are small outcrops of rhyolite tuff, the largest covering about 1/2 square km at the southern margin of the mesa.

This unit consists of a light pink, pumiceous tuff with pumice clasts generally no larger than 10 cm supported by a frothy, aphanitic matrix. Underlying the pumiceous tuff is a light purple to pink, aphanitic, weakly magnetic, welded tuff that contains less than 5 %, mm-scale sanidine phenocrysts and crops out as platy rubble. Petrographic analysis reveals a hypocrySTALLINE, inequigranular, eutaxitic texture and a rock composition of about 15 % sanidine, 15 % plagioclase and 10 % quartz phenocrysts no larger than 2 mm contained within a glass matrix. The matrix is substantially altered to clay. Obsidian nodules up to cobble size are sparsely distributed in the pumiceous tuff and as anomalous float on the basalt of Lobo Mesa. The largest nodules, many exhibiting a faceted appearance that suggests columnar jointing (figure 3), and greatest concentration of nodules, is near the large southern exposure of tuff.

Two potential sources exist for the tuff. Lobo Mesa is flanked by thick deposits of volcanic tuff that Hildreth and others (1984) identify as Huckleberry Ridge Tuff from the Yellowstone Plateau. Field comparisons of the tuff on Lobo Mesa and the Huckleberry Ridge Tuff along the West Fork of the Madison River reveal similarities including stratified

layers of pumiceous tuff overlying welded tuff, and conchoidal, platy fracture in the welded tuff. Compositional data (table 2) also show similarities in the tuff on the mesa with other tuff in the Gravelly Range and the Huckleberry Ridge Tuff on the West Fork of the Madison River. This evidence suggests that the tuff may be from the Yellowstone Plateau, or perhaps from other sources in the Gravelly Range.

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OXIDES (wt%)	LOBO MESA 1*	LOBO MESA 2*	WOLVERINE BASIN *	WEST FORK MADISON **
SiO <sub>2</sub>	74.22	74.82	75.00	75.40
Al <sub>2</sub> O <sub>3</sub>	13.42	13.01	12.84	12.70
FeO	1.65	1.71	1.84	1.71
MgO	0.21	0.25	0.02	<0.10
CaO	1.15	1.19	0.42	0.68
Na <sub>2</sub> O	3.57	3.53	3.88	3.34
K <sub>2</sub> O	5.63	5.34	5.78	5.42
TiO <sub>2</sub>	0.13	0.13	0.18	0.14
MnO	0.03	0.02	0.03	0.03
P <sub>2</sub> O <sub>5</sub>	N/A	N/A	N/A	<0.05

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Table 2. Major element geochemistry of Lobo Mesa, Wolverine Basin and West Fork of the Madison River rhyolite tuff.

\* Modified from Spaid-Reitz (1980).

\*\* Huckleberry Ridge Tuff, from Hildreth and others (1984).

Note: All values recalculated to 100% water free.

Alternately, the massive obsidian nodules associated with the tuff on the mesa were not observed in the Huckleberry Ridge Tuff. Dark, vitrophyric units appear in the Huckleberry Ridge Tuff exposed along the West Fork of the Madison River but all are distinctly flow banded and scoriaceous, unlike the massive nodules found on the mesa. Although no stoney rhyolite was observed on Lobo Mesa, the obsidian associated with the rhyolite tuff indicates viscous flow from a local source. If the tuff is derived from a local source, the largest, southern-most unit on the mesa, associated with the highest concentration of obsidian nodules, appears to be the most likely candidate.



Figure 3. Obsidian nodule from Lobo Mesa.



Spaid-Reitz (1980) places a maximum Rb/Sr date of 3.5 Ma on the tuff, but points out problems with her dating method that make the date questionable. Garson and others (1992) report an outlier of Huckleberry Ridge Tuff northwest of Lobo Mesa in the upper Ruby Basin, and suggest that it surged over the Gravelly Range from the Yellowstone volcanic field.

#### (2.8.3) Scoriaceous Agglomerate (Ta)

Near Hellroaring Creek this unit consists of red, subrounded, pebble to cobble size, self supporting, weakly cemented, basalt scoria clasts contained within a coarse, basaltic sand matrix. Alteration of the matrix to white clay minerals gives the rock a web-like appearance.

Scoriaceous agglomerate strongly cemented with basalt is at the eastern-most portion of the feeder dike system leading to the mesa. Small outcrops occasionally appear as members of the main basalt flow serving as markers that delineate flow units.

#### (2.8.4) Basalt Talus and Landslide Debris (Tt)

Thick colluvial deposits that flank Lobo Mesa are composed of unsorted, up to boulder sized, basalt talus mixed with clay and silt-rich soils. In this study they are included with the Tertiary System due to the well developed soil horizon compared to the modest lichen growth covering the Quaternary rock glaciers.

## **(2.9) Quaternary System**

### **(2.9.1) Rock Glaciers (Qr)**

In the northern part of the study area, below northeast facing cliffs, two rock glaciers composed of basalt talus are the source of springs that eventually feed into the Elk River. They occur at about 1,000 m elevation, are mostly barren of soil or plant cover and display the characteristic lumpy, lobate topography of a rock glacier.

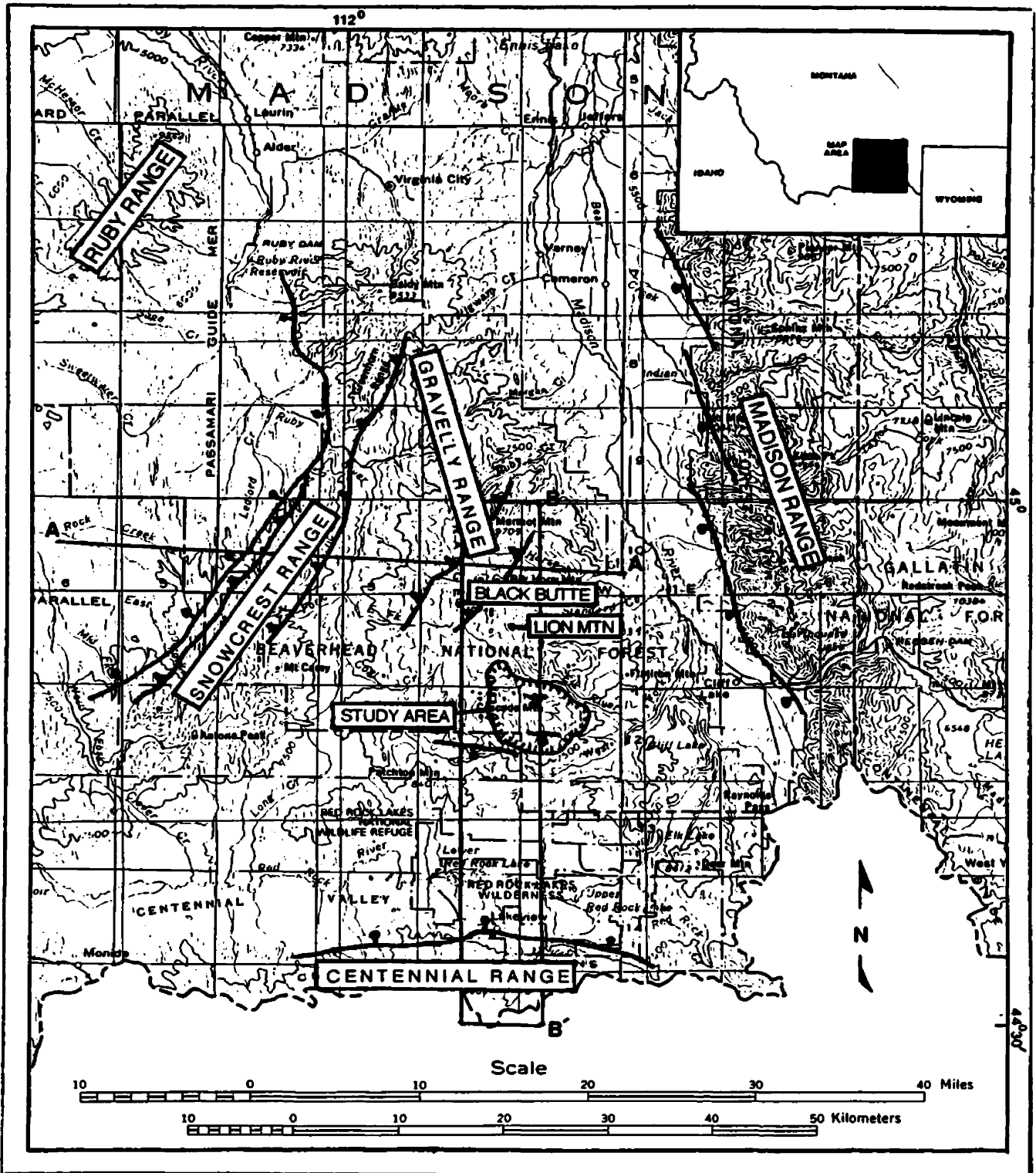


Figure 4. General tectonic map of region surrounding the study area. Modified from U.S. Geological Survey 1:500,000 topographic map of Montana. Structure data compiled from this study, Lemish (1948), Hadley (1969), Sheedlo (1984) and Witkind (1975).

### (3) STRUCTURAL FEATURES AND TECTONIC SETTING

#### (3.1) Precambrian Time

Evidence of Precambrian tectonism appears on Lobo Mesa at the angular unconformity between the Precambrian rocks and the overlying Paleozoic rocks. Shistosity of the Precambrian rock strikes northeast and dips generally less than 20 degrees northwest.

Basement surface irregularities in southwestern Montana produced by northwest, west and southwest trending structures of Proterozoic or Archean ancestry have been identified by Schmidt and others (1988) and Erslev (1983). The Precambrian structures, and reactivation of Precambrian faults, influenced the kinematics and geometry of later Montana thrust belt structures at the leading edge of the thrust belt in southwestern Montana (Schmidt and others, 1988; Sheedlo, 1984).

#### (3.2) Late Cretaceous-Early Paleocene Time

Structure within the Paleozoic section of Lobo Mesa is dominated by the late Cretaceous-early Paleocene deformation (Laramide Orogeny) that produced the Montana thrust belt. Lobo Mesa, and the Gravelly Range as a whole, lies near the eastern margin of the Montana thrust belt on the east limb of the Upper Ruby (Ruppel, 1982) syncline (figure 5), a structure formed during the Laramide Orogeny. Mean orientation of bedding in the Paleozoic section within the study area strikes

N23W and dips 9SW. Subsequent planation of the folded Paleozoic rocks, followed by burial of the section by the middle Miocene basalt of Lobo Mesa produced the angular unconformity that separates the two rock units.

Mann (1954) and Sheedlo (1984) mapped thrust faults of late Cretaceous-early Paleocene age in the central Gravelly Range and Snowcrest Range, respectively (figure 4). Regional cross-sections presented by Sheedlo (1984) show decollement of thrust sheets at the Mississippian-Devonian contact at depths of up to about 4 km below the western flanks of the Gravelly Range (figure 5). Mann (1954) notes that thrust faults in the central Gravelly Range grade into gentle folds and gradually flatten to the south. Parasitic folds in the Mississippian Madison Group within the study area show internal strain, but evidence of thrusting during Laramide deformation was not observed.

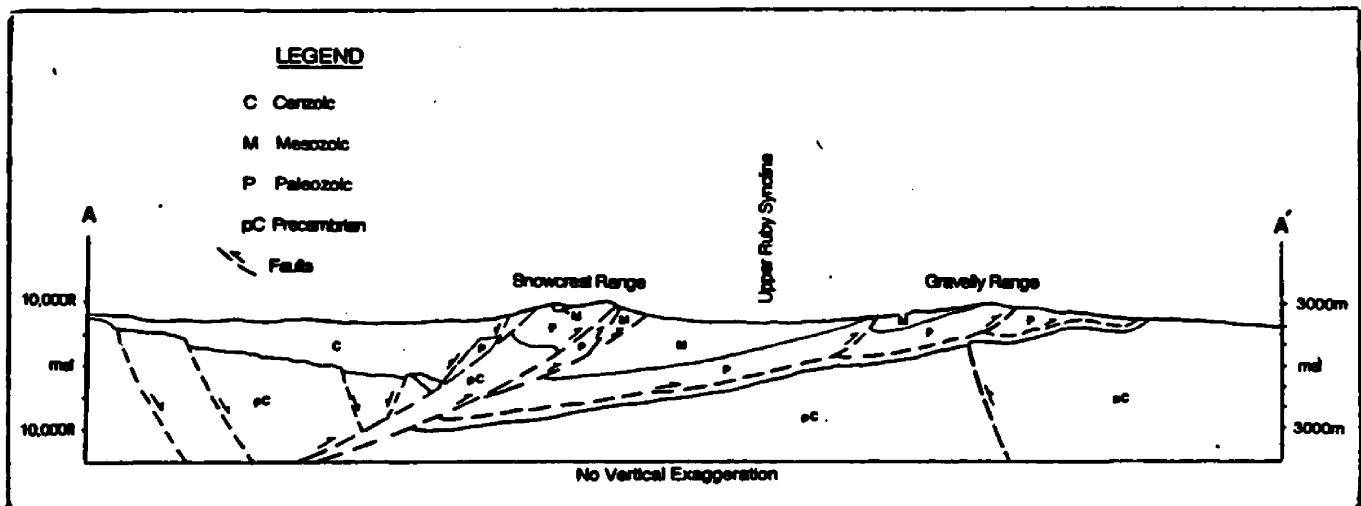


Figure 5. Cross-section of Upper Ruby syncline from A-A' on figure 4. Modified from Sheedlo (1984).

### (3.3) Quaternary Time

Lobo Mesa is host to west-trending, down-to-the-south normal faults that appear to be of Quaternary age. Middle Miocene basalt is offset by the southern-most fault. Vegetation is sparse on the southern-most fault scarp, and tectonically disturbed Paleozoic rocks on the hanging wall have a chaotic and angular outcrop pattern suggesting a brief erosional history. Juxtaposition of Precambrian rock against the Meagher-Pilgrim Formation along the southern-most normal fault indicates at least 30 m of offset. Brecciation marks the trace of both faults.

Stickney and Bartholomew (1987) state that two stress fields are currently acting to shape southwestern Montana. They conclude that Quaternary faults in southwestern Montana oriented generally to the west, similar to those observed on Lobo Mesa, are the result of Yellowstone hotspot tectonism. However, Quaternary faults oriented to the northwest are the result of Basin and Range tectonism (Eaton, 1979) that is now superimposed over Yellowstone Hotspot tectonism. Fritz and others (1989) believe that Quaternary age faults in southwestern Montana are primarily the result of Yellowstone hotspot tectonism, regardless of orientation. Based on the orientation and apparent age of the normal faults on Lobo Mesa, both hypotheses suggest the faults are the result of Yellowstone Hotspot tectonism.

Mann (1954) notes the absence of normal faults in the central Gravelly Range and suggests the area has existed as a relatively stable tectonic block since early Tertiary time. Seismic data and slip vector measurements presented by Bailey (1977) suggest to him that the Gravelly Range is acting as a single tectonic block, and that it appears to be on a north-northwest trajectory.

During Quaternary time at least 3,000 m of displacement has occurred on the west-trending Centennial fault (figure 4) south of Lobo Mesa (Schofield, 1980). Figure 6 illustrates a tectonic model developed as part of this study to account for structural features observed on Lobo Mesa and to place them in a regional context. Considerations for this model include: 1) the occurrence of west-trending, down-to-the-south normal faults on the mesa and other locations in the southern Gravelly Range, but not in the central part of the range; 2) the tremendous offset on the Centennial fault south of Lobo Mesa during Quaternary time; and 3) the apparent north-northwestern trajectory of the Gravelly Range as a single tectonic block.

Topographic map data is used to construct the surface and near surface profile for the model. Subsurface geometry of the Centennial fault is determined using the Chevron method described by Dula (1991). Gravity data presented by Schofield (1980) along 111.75 west longitude across the Centennial Valley, and hypocenter data (table 3) presented by Stickney

(written communication, 1992) within an area bounded by 45.00-45.50 north latitude and 111.75-111.85 west longitude constrain the Chevron method to develop the two potential geometries of the Centennial Fault in figure 6.

The model shows listric normal offset on the Centennial fault that flattens out at about 7 to 9 km below the crest of the Gravelly Range. Lobo Mesa holds a position in an extensional zone at the upper reach of a rollover anticline forming in response to offset on the Centennial fault.

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DEPTH(km)	ERROR(h)	ERROR(v)	LATITUDE	LONGITUDE
1.3	0.8	2.0	44.986	111.817
1.8	1.7	2.6	44.978	111.761
1.4	2.2	3.7	44.952	111.751
1.7	3.3	4.3	44.833	111.791
1.2	1.3	3.3	44.730	111.778
1.6	2.1	4.7	44.749	111.789
3.5	1.5	3.2	44.740	111.752
3.8	0.9	2.4	44.715	111.796
3.9	1.2	1.9	44.687	111.822
5.1	1.2	4.8	44.796	111.755
2.4	2.5	4.5	44.591	111.830
6.0	3.0	3.7	44.881	111.777
6.8	2.2	2.6	44.919	111.788
8.9	1.9	3.6	44.925	111.783
7.3	2.1	3.2	44.972	111.796
8.2	1.6	2.8	44.837	111.837
8.2	1.5	1.8	44.994	111.763

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Table 3. Hypocenter data from Stickney (written communication, 1992).



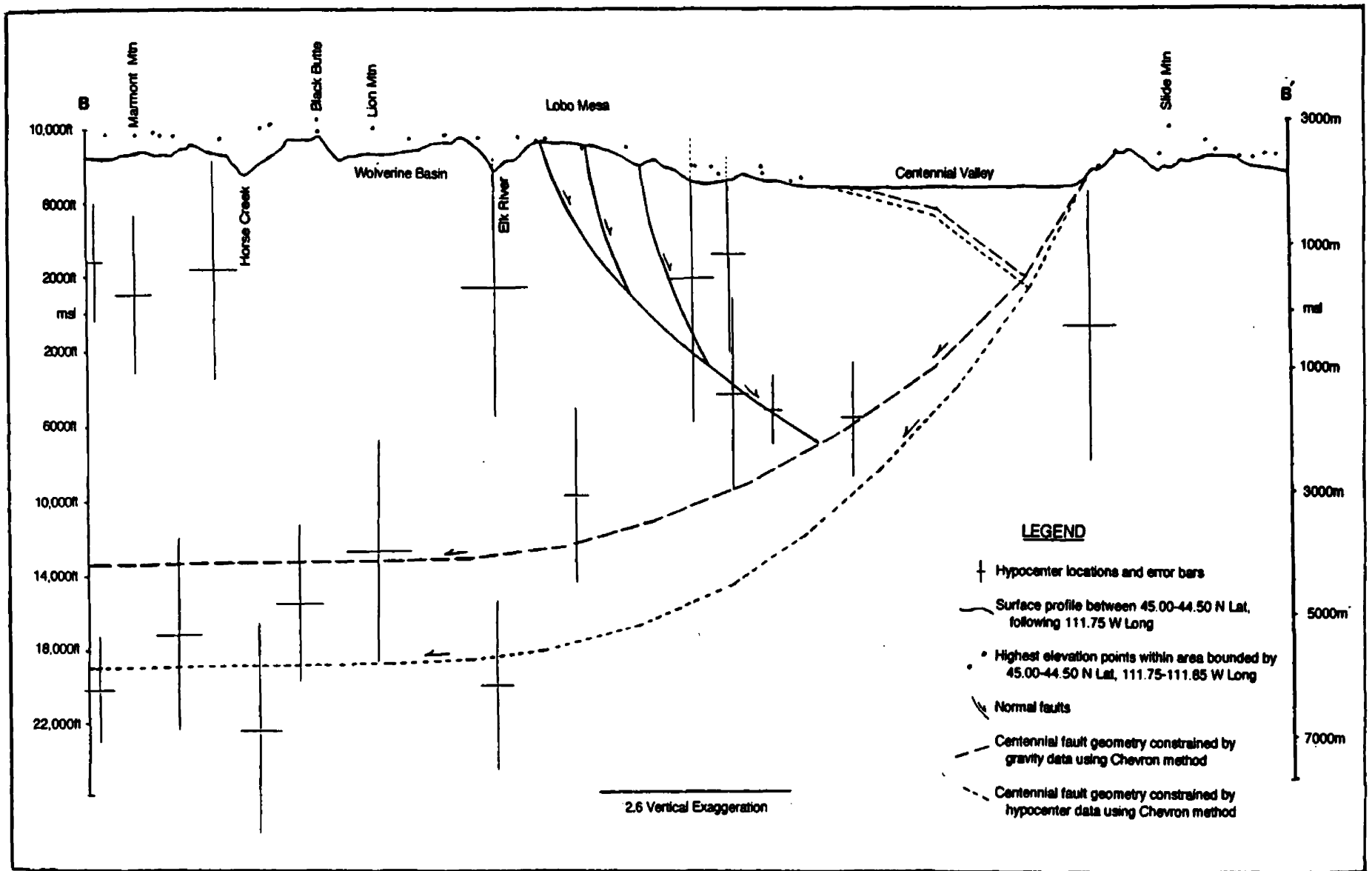


Figure 6. Tectonic cross-section of Quaternary deformation from B-B' on figure 4.

#### (4) GEOMORPHOLOGY

On the smallest scale, Lobo Mesa appears as a gently rolling landform with a south-trending slope of about 50 m/km. It is bordered by the deep canyons of Hellroaring Creek and Elk River to the north, Cascade Creek to the west and the West Fork of the Madison River to the south and southeast. The mesa serves as the headwaters for six streams including: Cascade Creek, Portal Creek, Lobo Creek, Tepee Creek, North Fork of Tepee Creek and Dirty Creek. They form a radial drainage pattern fanning from south to east along the flanks of the mesa.

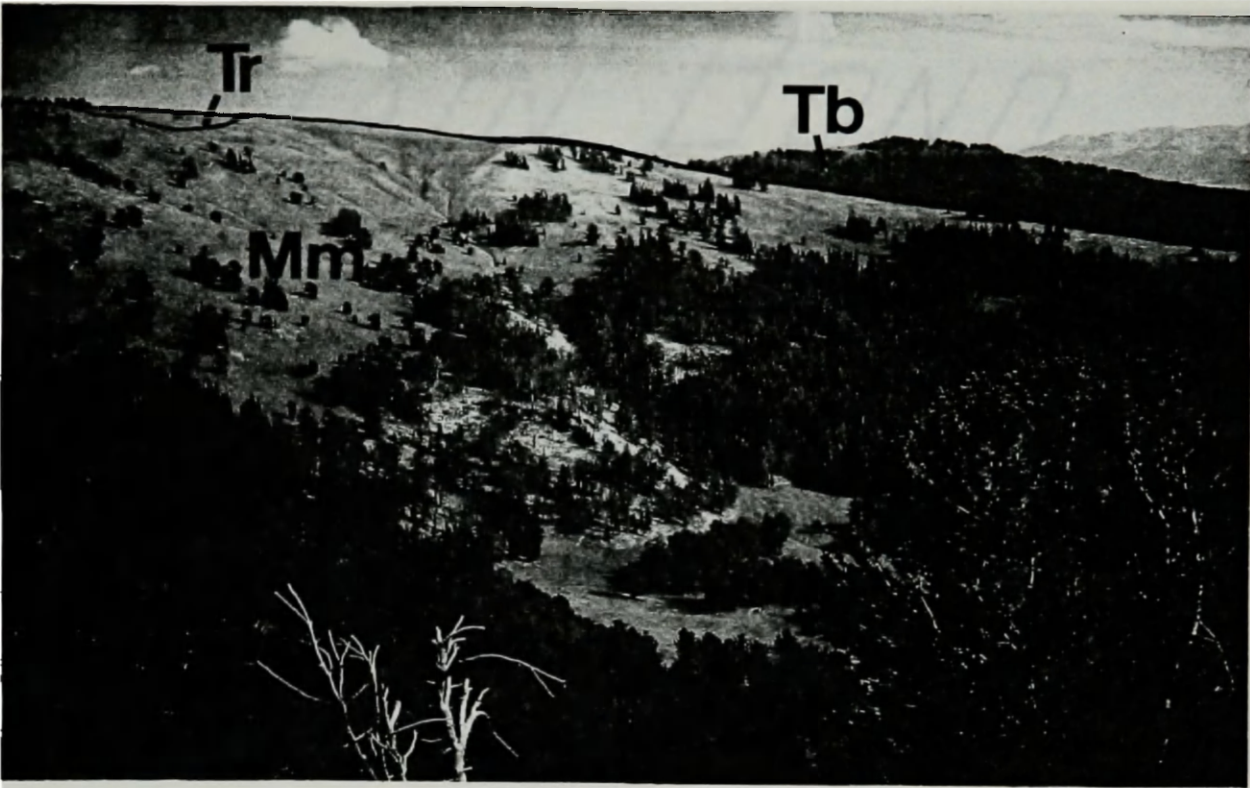
The dike and vent system feeding the middle Miocene basalt of Lobo Mesa appears at the northwest corner of the mesa. The dikes are linear topographic features that converge on the highest point, a geomorphic expression similar to that of the dike and vent system at Lion Mountain. The basalt flows, traveling southeast across Lobo Mesa, filled paleovalleys and feathered out over topographic highs. A basalt-filled paleovalley seen along Cascade Creek exhibits about 180 m of relief (figure 7).

Evidence of Quaternary mass wasting is present on a large scale at several locations. Landslides that face the southern slopes of the Elk River canyon are composed of unvegetated rubble, and blocks of Paleozoic rocks that once were timber-covered slopes (figure 8). Below the confluence of the Elk River and Hellroaring Creek, slide material extends to the Elk

River creating a steep, v-shaped gorge with slide debris on the north side and Precambrian rocks on the south side.

Slumps and sinkholes are found within the Tertiary basalt talus mapped along Cascade Creek. The unvegetated head scarp of one slump reveals a clay-rich soil. Springs flow from the base of the scarp. Figure 9 shows a funnel-shaped sinkhole in this unit about 5 m in diameter with the tops of dead and dying trees protruding from its center. The basalt talus is underlain by Mississippian Madison Group limestone suggesting the sinkholes are the result of karst processes.

Sinkholes are also evident in the Permian Phosphoria Formation that forms Crater Ridge in the northwestern-most section of the study area (figure 10). Undrained depressions in the upper quartzite and bedded chert units of the formation, ranging in size from meters to tens of meters, abound along the crest of the ridge.



**Figure 7. Topography of middle Miocene surface along Cascade Creek.**



**Figure 8. Landslides on south-facing slopes of the Elk River canyon.**



**Figure 9. Sinkhole in Tertiary basalt talus along Cascade Creek.**



**Figure 10. Sinkholes in Phosphoria Formation on Crater Ridge.**

## **(5) DISCUSSION AND ADDITIONAL WORK**

### **(5.1) Stratigraphy**

A notable difference between the stratigraphy on Lobo Mesa compared to Lion Mountain and Black Butte in the central Gravelly Range is the lack of cross-bedded, Oligocene tuffaceous mudstone and Eocene-Oligocene gravel (figure 2). Gutmann and others (1989) determined a biotite K-Ar date of 31.4 +/- 0.7 million years for the tuffaceous mudstone of Lion Mountain making it correlative in time and lithology with the Renova Formation first identified by Kuenzi and Fields (1971) in the Jefferson basin to the north. The mudstone is about 120 m thick at Lion Mountain. Mann (1954) estimated an Eocene-Oligocene age for the gravel based on fossil evidence.

Erosion may explain the absence of tuffaceous mudstone and gravel beneath the late Miocene basalt of Lobo Mesa or, considering the Quaternary tectonic model presented in this thesis, Lobo Mesa may have stood as a topographic high before Quaternary tectonism and never buried by Oligocene sediment. The later case suggests that the Oligocene sediment intruded by Lion Mountain and Black Butte basalt (Gutmann and others, 1989) existed within a localized Oligocene basin; the Lion Mountain basalt flowing over the land surface preserving Oligocene sediment; the Black Butte basalt only breaching the surface, indicated by the presence of scoriaceous agglomerate and volcanic bombs on top of and immediately adjacent to the butte, but never flowing over and preserving the sediment.

Past studies by individuals previously cited provide an abundance of detailed stratigraphic data on Precambrian to Quaternary rocks and sediments in the Gravelly Range. The stratigraphic units generating the greatest debate are those belonging to the Tertiary system. This study reveals that Lobo Mesa is the youngest basalt volcanic center currently known in the Gravelly Range. The source and age of the rhyolite tuff of Lobo Mesa, and the source and depositional history of Tertiary units in the Gravelly Range, including carbonate conglomerate, tuffaceous mudstone and gravel, remains largely unresolved.

#### (5.2) Structure

Hypocenter data is used in the Quaternary tectonic model (figure 6) to aid in defining the plane of the Centennial fault. Limited data and poor hypocenter resolution does not lead to a clear picture of the fault geometry in the model. The Montana Bureau of Mines and Geology plans to place a new seismic recorder south of Lobo Mesa during the summer of 1992 (Stickney, personal communication, 1992). Data from this instrument are expected to improve the quality of future hypocenter calculations from seismic events in the Gravelly Range and Centennial Valley.

On a scale beyond the model presented in this study, a complete three dimensional structural evaluation needs to be

conducted on the southern Gravelly Range from the Ruby River to the Madison River. Lobo Mesa is only a small piece to the geologic puzzle of southwestern Montana, but its apparent position at a transition zone where late Cretaceous-early Paleocene structures are being overprinted by Quaternary structures makes it a good focal point from which to expand future studies.

### (5.3) Geomorphology

The drainage pattern on Lobo Mesa that radiates away from the source of the basalt, and the topography of the middle Miocene surface, suggest that local volcanism created certain landforms during middle Miocene time. However, fresh scarps on sinkholes, landslides and slumps are evidence that Lobo Mesa is part of a landscape still actively in the making.

The tectonic model presented in this study places Lobo Mesa in a region of active extension along the upper reach of a rollover anticline. This provides a mechanism for the development of certain Quaternary landforms. Sinkholes in the basalt talus overlying Madison Group limestone appear to be the result of karst processes; slumps, the result of movement in water-saturated, clay-rich soil; and the landslides along the Elk River may be caused by undercutting the steep canyon walls. However, the landforms not readily defined by these basic geomorphic processes are the fractured bedrock and sinkholes on Crater Ridge. According to Ritter



(1986), karstification is a process usually associated with rock that is susceptible to solution, primarily carbonate rock. On Crater Ridge, sinkholes are developed in the quartzite and bedded chert of the Phosphoria Formation. Mann (1954) observed thin limestone and dolomite units at the base of the formation. Solution of the underlying carbonate rock may cause the quartzite and chert to collapse and form a karst landscape. A problem with this hypotheses is that the fractured and collapsed appearance of the formation is localized on Crater Ridge. To the north and south it appears relatively unfractured and without sinkholes. The anomolous landforms on Crater Ridge may be evidence of localized deformation caused by extension along the upper reach of the rollover anticline. If the landforms on crater ridge can be attributed to extensional forces, perhaps the Quaternary landslides along the Elk River canyon, and the formation of the canyon itself, may also be partly a function of this stress and not related exclusively to erosion.

## (6) CONCLUSIONS

The principle conclusions of this study are: 1) the basalt of Lobo Mesa is derived from a west-northwest trending dike and vent system located along the northwestern margin of the mesa; 2) at least five flow units have covered the mesa; 3) a whole rock K-Ar date on one of the flows shows a late Miocene age of 16.9 +/- 0.3 million years making Lobo Mesa the youngest known volcanic center in the Gravelly Range; 4) the age and source of the rhyolite tuff on Lobo Mesa remains indeterminate; 5) Lobo Mesa, along with the southern portion of the Gravelly Range, has been down-faulted and tilted to the south during Quaternary time as part of a rollover anticline that is forming in response to listric normal offset on the Centennial fault; 6) down-to-the-south normal faults on Lobo Mesa are antithetic to the Centennial fault; and 7) topography on the middle Miocene surface, and the radial drainage pattern of Lobo Mesa, are middle Miocene landforms created by volcanic deformation.

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## (8) APPENDIX A

### (8.1) Resource Evaluation

Atwood and Atwood (1945) state that small amounts of gold have been recovered from the gravel along the crest of the Gravelly Range. Christie (1961) reports on placer gold recovered from the West Fork of the Madison River totaling a reported 32.63 fine ounces that may have come from the high-level gravel. Placer gold potential was not considered during this study due to the absence of high-level gravel on Lobo Mesa. The silicified breccia present along the trace of the southern-most normal fault on the mesa held promise of a hydrothermal deposit, but an assay of breccia from sample location 2 (map, back pocket) yields Au=<.001 ounces /ton, Ag=0.05 ounces/ton (Warmouth, personal communication, 1992).

Hydrocarbons, detected by a pervasive petroliferous odor, are present in the early to middle Paleozoic rocks on Lobo Mesa. Thin section evaluation of the sparry dolomite of the Devonian Jefferson Formation and the Cambrian Meagher-Pilgrim Formation show the rock to consist of about 10 to 20 % pore space surrounded by euhedral dolomite crystals. The dolomite may be a good reservoir rock for hydrocarbons, but the structural position of the mesa on the eastern limb of the Snowcrest syncline which was beveled by Tertiary erosion, does not provide a trap or seal.

Mann (1954) observed phosphatic shale in the lower portion of the Permian Phosphoria Formation measuring about 9 m thick

north of Lobo Mesa. Within the study area, the lower units of the Phosphoria Formation are covered by chert and quartzite talus making potential phosphate resources indeterminable.