ı
,
s
l.
n
),
ie
on
an
nd
an:
eol.
the
mo-
ish,
orn-
shop
nge:

Studies in Volcanology — RR Coates, R. L. Hay + C.A. Anderson (
Geological Soc of Amer Mem 116 p 557-576
1968

# Overlapping Plutonism, Volcanism, and Tectonism in the Boulder Batholith Region, Western Montana

G. D. ROBINSON
*U.S. Geological Survey, Denver, Colorado*

M. R. KLEPPER
*U.S. Geological Survey, Washington, D.C.*

J. D. OBRADOVICH
*U.S. Geological Survey, Denver, Colorado*

## ABSTRACT

It is well known that the Boulder batholith region experienced intensive plutonism, volcanism, and tectonism that all began in Late Cretaceous time, after at least 700 m.y. of structural and igneous inactivity except for sporadic epeirogeny. Recent stratigraphic, structural, paleontologic, and, especially, radiometric evidence makes it possible to date these dynamic events rather closely. The time relations that are revealed do not form a simple sequence of volcanism-folding-thrusting-batholith emplacement, as has often been supposed, but involve an intertwined complex.

Significant volcanism began ~ 85 m.y. ago in late Coniacian or early Santonian time, with deposition of the thick, local tuffaceous Slim Sam Formation. Volcanism climaxed from 77 to 79 m.y. ago, in early Campanian time, when the region was buried under at least 10,000 feet of calc-alkalic volcanic and volcaniclastic rocks, which included many sheets of welded tuff — the Elkhorn Mountains Volcanics —, and a vast amount of contemporaneous ash was airborne beyond the region. Major volcanism ceased ~ 73 m.y. ago,

late in the Campanian, not to recur until early Eocene time, ~ 50 m.y. ago.

The bulk of the batholith was emplaced beneath and within the volcanic edifice in early and middle Campanian time, during a 6 m.y. span from 78 to 72 m.y. ago, and some leucocratic masses were intruded during the next few million years, so that the whole batholith was emplaced within about 10 m.y.

Folding at and near the site of the batholith began in late Coniacian or Santonian time and culminated before middle Campanian time; the main folding north and east of the batholith was post-Campanian, probably Maestrichtian. Thrusting began before middle Santonian time, and recurred intermittently well into the Maestrichtian, or even a little later.

Thus volcanism, plutonism, folding, and thrusting began and ended within a few million years of each other, during the last 20 m.y. of the Cretaceous. Major folding, thrusting, and volcanism started about the same time, though not always at the same places, and a little earlier than plutonism. In any given locality, volcanism ended before major folding; the climax of plutonism followed the climax of volcanism; thrusting preceded and accompanied plutonism near the batholith, but followed plutonism farther away; thrusting ended a little later than folding. These dynamic processes so closely related in time and space must also be genetically related in the Boulder batholith region. Gilluly's (1965) conclusion that the orogeny which produced the great Cretaceous thrusts of Montana was "essentially without plutonic associations" is not tenable.

## CONTENTS

# INTRODUCTION

In GSA Special Paper 80, James Gilluly (1965, p. 5) introduced his subject by saying: "The greatly improved map coverage recently available together with the increasing number of radiometric dates on both plutonic and volcanic rocks permit a more detailed appraisal of the relations in time and space between tectonism, plutonism, and volcanism than has hitherto been possible for the western United States." One part of the western United States to which Gilluly's statement applies particularly well is the Boulder batholith region (Fig. 1). During the past 15 years this region has received much attention from geologists, geophysicists, and geochronologists of the U.S. Geological Survey and of several universities; and not a little attention from that remarkable private research institution comprised of the late Adolph

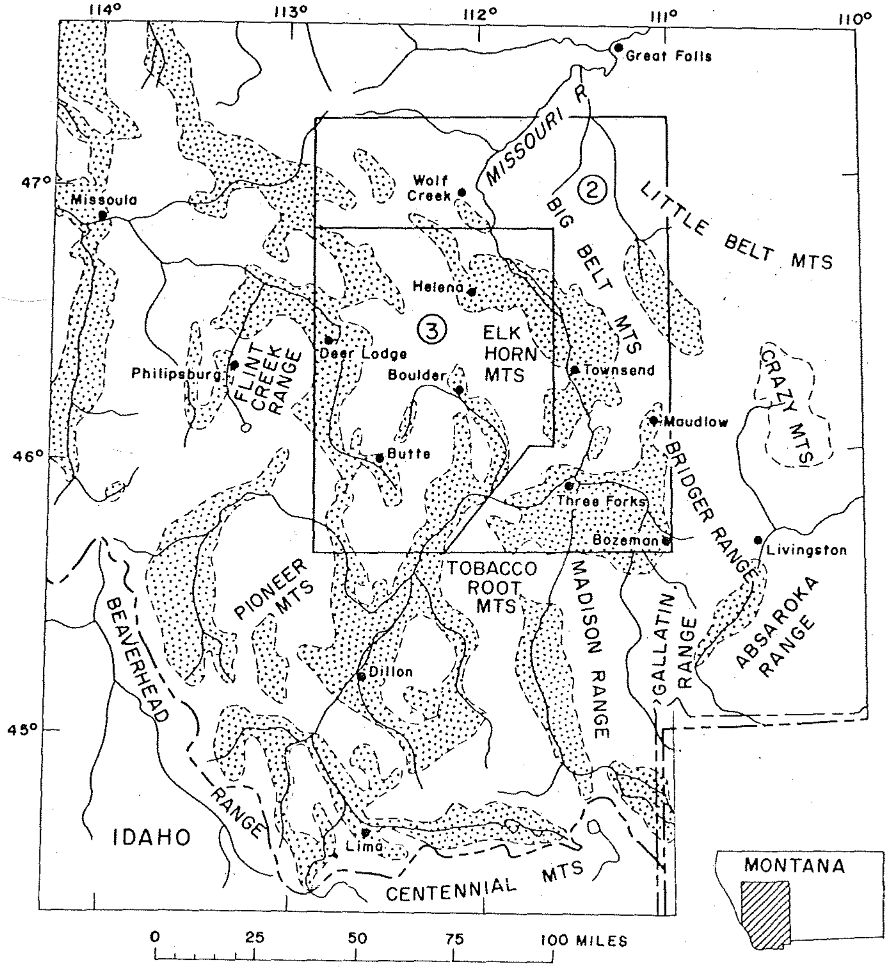


Figure 1. Index map of southwestern Montana. Intermontane valleys are stippled; areas of Figures 2 and 3 are heavily outlined.

Knopf and his wife, Eleanora B. Knopf. Much has been published, but many valuable data have not, and little has appeared in the way of regional syntheses.

The present occasion seems a good time to bring together what is known about the time relations of plutonism, volcanism, and tectonism in this 7000-square-mile segment of the Northern Rocky Mountains, particularly as we believe these phenomena to be more intimately related than does Gilluly, whose above-cited review article is bound to be widely influential. Considerable information, which includes many new radiometric age determinations, is available now that was not available to Gilluly.

The Boulder batholith itself crops out over about 2200 square miles in the southwestern part of the area we have called the Boulder batholith region (Fig. 2). The boundaries of the region have been chosen to embrace virtually all remnants of the Elkhorn Mountains volcanic field as well, because these volcanic rocks are chemically consanguineous with the batholith (Klepper and others, 1957, p. 34, 44–50; Robinson, 1963, p. 88–102), and the batholith is emplaced almost wholly within the volcanic edifice. Therefore, batholith and volcanics are at least broadly related. The west edge of the region is placed at the longitude of Deer Lodge Valley to avoid involvement with the Philipsburg batholith in the Flint Creek Range (Fig. 1).

The region has a remarkably complete geologic record, which begins with Precambrian high-grade metamorphic rocks perhaps initially more than 2000 m.y. old, but recrystallized 1600 ± 100 m.y. ago (Giletti, 1966). The first regional angular unconformity after that event separates the sedimentary rocks of the Belt Supergroup from the metamorphic rocks; it is much more than 1000 m.y. old, to judge by current radiometric work on glauconite (K-Ar and Rb-Sr) and Rb-Sr whole-rock dating of argillaceous Belt rocks (Obradovich and others, 1966). In late Precambrian time, 700 to 800 m.y. ago (unpublished K-Ar determinations on pyroxene by R. F. Marvin, 1965), many thick and extensive gabbroic sills were emplaced. Thereafter, for more than 700 m.y., the region experienced no intrusive or extrusive igneous activity, and no deformation other than episodes of mild epeirogeny. (For summaries of geologic history, see Klepper and others, 1957, p. 4, and Robinson, 1963, p. 10.) Then, beginning in Late Cretaceous and perhaps extending into earliest Tertiary time, the Elkhorn Mountains Volcanics were erupted, the Boulder batholith and its numerous satellitic bodies were intruded, and the rocks of the region were broken by block faults, contorted into tight folds, and rent by thrusts. Except for the radiometric work cited above, all this is familiar and needs no elaboration.

Not familiar, however, are the inter-relations among plutonism, volcanism, and tectonism in the region, and it is our purpose to examine these. It turns out that these relations do not form a simple and rather long sequence of volcanism-folding-thrusting-batholith emplacement as has often been suggested or implied (*see* especially Billingsley, 1916, p. 35; Billingsley and Grimes, 1918, p. 357; Pardee and Schrader, 1933, p. 12–20, 24–25; Alexander, 1955, p. 98; Knopf, 1957, p. 87–88; Eardley, 1962, p. 321, 329–333), but rather an intertwined complex within about 20 m.y. in Late Cretaceous time. This interpretation is not an original inspiration, but has evolved from piecemeal contributions by many workers. It has been tentatively expressed before, but without adequate factual base (*see,* for example, Robinson, 1963, p. 2; Smedes, 1966, p. 1–2; Robinson and Marvin, 1967, p. 606) and it was adopted in a recent analysis of batholiths by Hamilton and Myers (1967, p. C7–C9, C24). We shall try to document this complex overlapping by successively sketching the Late Cretaceous chronology of plutonism, of volcanism, and of tectonism; and finally by viewing plutonic, volcanic, and tectonic history simultaneously against the radiometric time scale of Gill and Cobban (1966, p. A35).

We are indebted to W. A. Cobban, J. R. Gill, R. I. Tilling, and especially H. W. Smedes for aid in preparing this paper, and to James Gilluly, Warren Hamilton, and H. W. Smedes for helpful criticism.

## PLUTONISM

The Boulder batholith is a composite mass comprising a dozen or more plutons of holocrystalline, generally medium- to coarse-grained, calc-alkalic rocks that range in composition from syenogabbro to alaskite. Its average composition is close to quartz monzonite or granodiorite. The main body is flanked by many satellitic plutons, dikes, and sills that are similar in composition and texture to rocks of the batholith. Known intrusive sequences are in the direction of increasing silica content. Most of the plutons can be conveniently assigned to one of four groups: mafic rocks, granodiorite, the Butte Quartz Monzonite, and leucocratic rocks (Fig. 3). At least 75 percent of the exposed batholith consists of a single large body, the Butte Quartz Monzonite, which is coextensive with and indistinguishable from the Clancy Granodiorite (Knopf, 1957).

The batholith has been thought to be as old as Jurassic and as young as Miocene (*see* Knopf, 1957, p. 82–83 for discussion of early work). Recent stratigraphic, paleontologic, and radiometric studies demonstrate together that the batholith was emplaced and cooled in Late Cretaceous time. The youngest rocks invaded are the Elkhorn Mountains Volcanics; sedimentary interbeds near both top and bottom of the formation have yielded scanty fossils of late Late Cretaceous, probably Campanian (Judith River Formation) age (Klepper and others, 1957, p. 37–38). The oldest fossiliferous rocks demonstrably younger than the batholith are middle or upper Eocene basin deposits that contain detritus from the exposed batholith (Robinson, 1963, p. 75–76).

Radiometric data yield a narrower age range. Knopf (1964) reviewed the isotopic information available in 1963, principally K-Ar ages on biotite and hornblende from the northernmost part of the batholith. He concluded that the batholith is entirely of Late Cretaceous age, and estimated that em-

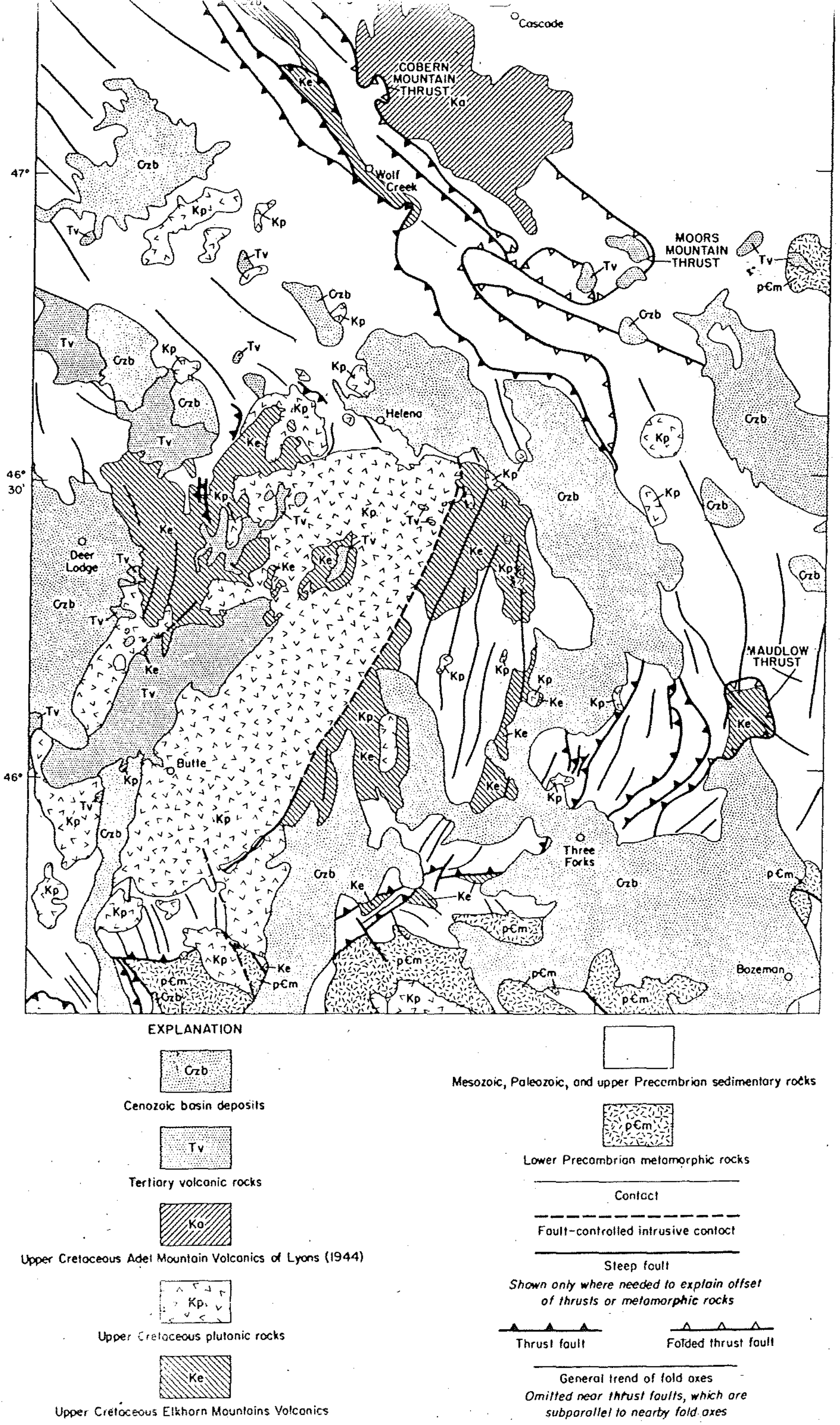


Figure 2. Generalized geologic map of the Boulder batholith region.

placement of the northern part took from 7 to 8 m.y. Now, many additional K-Ar ages on biotite and hornblende representing the entire batholith have been determined, mostly by F. W. McDowell (1966, unpublished Ph.D. thesis, Columbia University) and by Obradovich and R. F. Marvin, *in* Tilling and others (in press); some of the earlier determinations have been refined. The entire suite of isotopic ages available in 1966 is assembled and critically evaluated by Tilling and others; the remainder of this section is based on their study, which should be consulted for details. They accept 45 determinations on 26 samples as analytically reliable; the localities represented by these are shown on Figure 3. On Figure 4, the age data are grouped according to the map units of Figure 3 and arranged in known or inferred intrusive sequence. The data indicate that the bulk of the batholith crystallized during a span of no longer than 6 m.y., from 78 to 72 m.y. ago, although small bodies of leucocratic variants continued to crystallize within the mass for a few million years more, so that the entire batholith crystallized in about 10 m.y. On the time scale adopted here, this span embraces most of the Campanian Stage (~ 82 to 71 m.y. ago) and part of the Maestrichtian Stage.

## VOLCANISM

The volcanic chronology of the region is not nearly so clear as is the plutonic chronology, but a fairly consistent story emerges from a combination of published stratigraphic and paleontologic data with new radiometric information.

The first indigenous volcanism of any consequence is represented by a flood of coarse volcanic detritus in the Slim Sam Formation (Klepper and others, 1957, p. 28–31). In the northern Elkhorn Mountains, the formation is as much as 1200 feet thick, but is only locally present; thinner sequences of rocks equivalent to the Slim Sam Formation in lithology and age crop out in the Maudlow basin (Skipp and Peterson, 1965, member A, intermediate volcanic and volcaniclastic rocks) and near Wolf Creek (Schmidt, 1963, clastic volcanic rocks of lower unit, Two Medicine Formation). The lower part of the Slim Sam has yielded marine invertebrate remains like those of the Niobrara Formation (Klepper and others, 1957, p. 29), which is of Santonian age.

The Elkhorn Mountains Volcanics succeed the Slim Sam Formation, in some places gradationally, in other places unconformably. Where the Slim Sam is absent, Elkhorn Mountains Volcanics lie unconformably on sedimentary rocks as young as Santonian (middle Niobrara) (Klepper and others, 1957, p. 28).

The Elkhorn Mountains Volcanics are remnants of a volcanic plateau that once covered most or all of the area shown in Figure 2, and probably several thousand square miles more (Smedes, 1966, p. 21). In the central part of the plateau, the formation was originally more than 10,000 feet thick. It comprises a lower member mainly of andesitic and rhyodacitic autoclastic

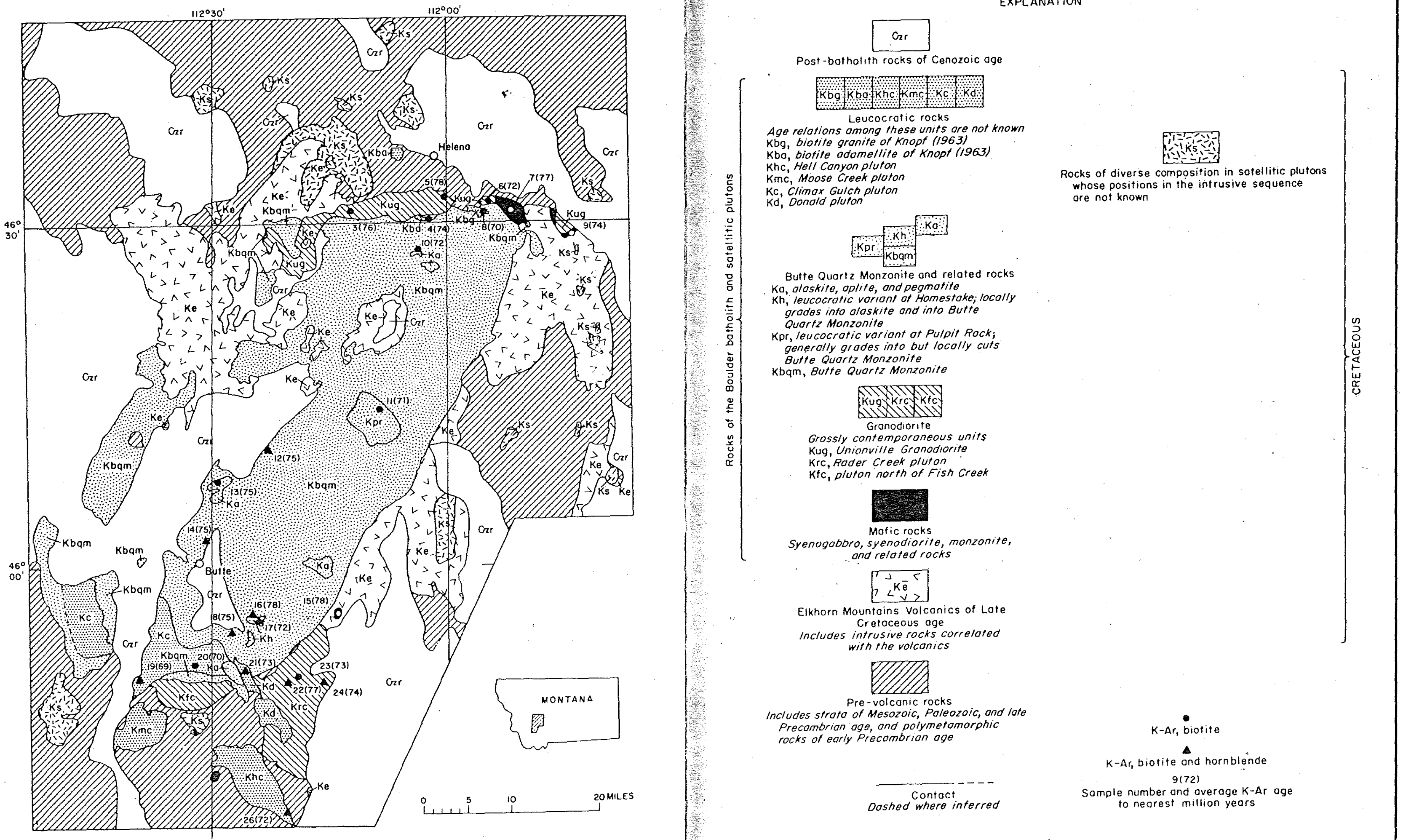


Figure 3. Geologic map of the Boulder batholith and vicinity showing location of rocks dated by K-Ar method (slightly modified from Tilling and others, in press).

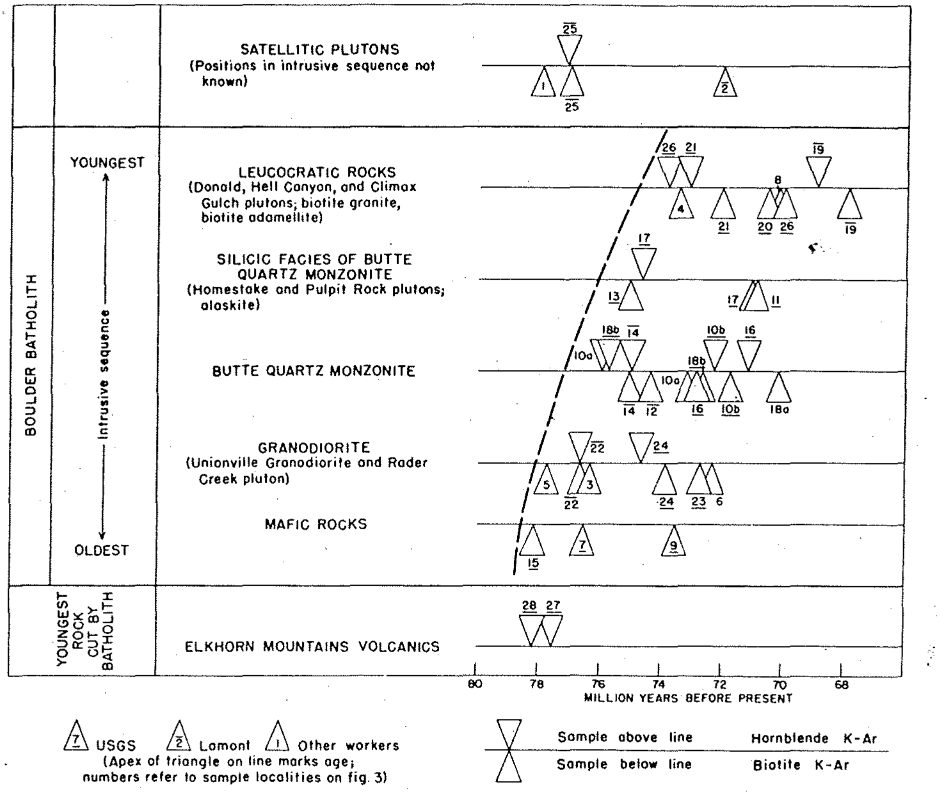


Figure 4. K-Ar ages of minerals from the Boulder batholith and the Elkhorn Mountains Volcanics. Ages of batholith minerals are grouped according to the map units of Figure 3 and arranged in known or inferred intrusive sequence (after Tilling and others, in press).

breccia and lava; a middle member characterized by rhyolitic welded tuff in extensive sheets; and an upper member consisting mainly of erosional debris from the lower two members.

On stratigraphic and paleontologic evidence, the Elkhorn Mountains Volcanics are largely, perhaps wholly, of Campanian age. In the type area, these volcanics, as noted before, lie on rocks as young as Santonian and contain Late Cretaceous, probably Campanian, fossils. The top of the formation has everywhere been removed by erosion, and its upper age limit is therefore uncertain, but the formation is distinctly older than the unconformably overlying lower Eocene Lowland Creek Volcanics (Smedes, 1962; Smedes and Thomas, 1965).

More geologic dating evidence comes from rocks correlated with the Elkhorn Mountains Volcanics on the eastern and northern perimeters of the region. In the northeastern corner, correlative welded tuffs, lava flows, and volcaniclastic sedimentary rocks are underlain by and interbedded with terrigenous sedimentary rocks of the Two Medicine Formation of Campanian age (Schmidt, 1963 and 1966; Viele and Harris, 1965). In good exposures on the Dearborn River 25 miles northwest of Wolf Creek, welded tuffs occur throughout a stratigraphic sequence more than 2000 feet thick that represents the range zones of *Baculites obtusus* to *B. compressus* or *B. cuneatus* (J. R. Gill and W. A. Cobban, written commun., 1966). The Two Medicine Formation is overlain by the St. Mary River Formation of Campanian and Maestrichtian age, but lacks Elkhorn Mountains-type components. In the Crazy Mountains basin just southeast of the batholith region, coarse detritus that includes pebbles of welded tuff of the Elkhorn Mountains Volcanics is a major component of the thick and extensive Livingston Group of Late Cretaceous age (Roberts, 1963 and 1965), as Billingsley (1915, p. 35) recognized long ago. Such debris is abundant in even the oldest rocks of the group, the nonmarine Cokedale Formation, which contains early Campanian (Claggett Formation) vertebrate and plant remains (Roberts, 1963, p. B90), and thereby demonstrates that at least part of the middle welded-tuff member of the Elkhorn Mountains Volcanics is early Campanian or older.

Campanian age is consistent with the sparse radiometric data. Hornblende phenocrysts from autoclastic breccia near the base of the formation in Jefferson Canyon (Fig. 5, no. 28), southeast of the batholith, have a mean K-Ar age of about 78 m.y. (Table 1); hornblende phenocrysts from high in the lower member, near the top of Cliff Mountain, 11 miles east of Deer Lodge (Fig. 5, no. 27; Ruppel, 1961), also have a K-Ar age of about 78 m.y. (Table 1). This locality that is in the roof of the batholith, but is more than 3 miles from the nearest exposure of plutonic rocks, is estimated to be at least 3000 feet above the top of the batholith, and the rocks show no signs of metamorphism. Biotite and plagioclase from still-glassy welded tuff of the middle member at two widely separated localities — near Wolf Creek (Fig. 5, no. 30) and west of Three Forks (Fig. 5, no. 29) — have K-Ar ages close to 73 m.y. (for details *see* Robinson and Marvin, 1967).

At first glance these numbers appear to be straightforward, but the 73-m.y. ages are incompatible with the field evidence. The 78-m.y. hornblende ages from the lower member seem reasonable enough, but an age as low as 73 m.y. for the middle member does not fit its stratigraphic position: at least the

TABLE 1. NEW K-AR AGE DATA ON HORNBLENDE FROM THE ELKHORN MOUNTAINS VOLCANICS*

| Map No. (Fig. 5) | Sample No. | $K_2O$† (percent) | Radiogenic $Ar^{40}$ (moles $gm^{-1} \times 10^{-11}$) | Radiogenic $Ar^{40}$ (percent) | Age (m.y.) |
|---|---|---|---|---|---|
| 27 | D1564 | 0.988 | 11.55 | 90 | 77.6 ± 2.4 |
| 28 | D1567A | 0.829 | 9.84 | 94 | 78.8 ± 2.4 |
| 28 | D1567B | 0.834 | 9.75 | 95 | 77.6 ± 2.4 |

Decay Constants: $K^{40}$: $\lambda\varepsilon = 0.584 \times 10^{-10}$ year$^{-1}$
$\lambda\beta = 4.72 \times 10^{-10}$ year$^{-1}$
$K^{40} = 1.22 \times 10^{-4}$ gm/gmK

*Analyst: J. D. Obradovich
†Duplicate isotope dilution analyses

lowest part of the member must be of early Campanian (Claggett Formation) age (from 81 to 77 m.y.) or older, to have provided the welded-tuff clasts in the Cokedale Formation; further, and perhaps more significant, the dated welded tuff from Wolf Creek is interbedded with terrigenous deposits of the *Baculites obtusus* zone (J. R. Gill and W. A. Cobban, written commun., 1966), which is three baculite zones higher than strata dated as 81 ± 2 m.y. and 13 zones lower than strata dated as 75 ± m.y. (Gill and Cobban, 1966, Table 2, p. A35). The anomalously young determinations are on biotite and plagioclase, which tend to retain argon less well than hornblende (Hart, 1964). It seems likely, therefore, that the apparent ages of these welded tuffs are minimum ages, and that the rocks are really several million years older.

Robinson and Marvin (1967, p. 607 and Table 2) also report K-Ar ages of biotite (83 ± 2 m.y.) and plagioclase (71 ± 7 m.y.) phenocrysts from a somewhat devitrified welded tuff near Maudlow. We have not taken these internally inconsistent numbers into account in this paper.

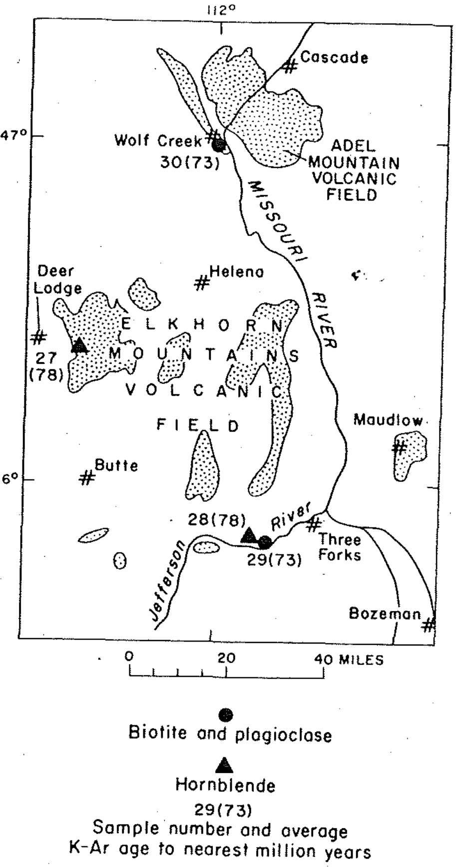


Figure 5. Locality map of K-Ar age determinations from the Elkhorn Mountains Volcanics and correlative rocks (stippled pattern).

The available radiometric age data thus permit the interpretation that much of the Elkhorn Mountains Volcanics was erupted in one or two million years. The occurrence of other welded tuffs as high as the range zone of *Baculites compressus* or *B. cuneatus,* however, suggests that the Elkhorn Mountains vents were still active from 73 to 75 m.y. ago (Gill and Cobban, 1966, p. A35). Accordingly, the volcanics were probably being erupted during a span of 5 m.y. or more within the Campanian Stage, whether or not the isotopic ages of the welded tuffs at Three Forks and Wolf Creek are adjusted.

A major product of Elkhorn Mountains volcanism, possibly rivaling the volume of the volcanic plateau itself, may be the rhyolitic ash that abounds in the Upper Cretaceous marine and paralic sedimentary rocks of the continental interior east of the volcanic field. But other volcanic centers to the west may have been active at the same time, and there is no way yet known to identify uniquely the source or sources of this debris, as the prodigious but futile efforts of Slaughter and Earley (1965, p. 78-86) attest. Consequently, the Upper Cretaceous ash is not considered further here, beyond adding that meaningful analysis of the mechanics of emplacement of the volcanic and plutonic rocks of the region must ultimately take account of the vast bulk of magma (*see* Hamilton and Myers, 1967, p. C9 for volume estimates) represented by this far-flung detritus. Its existence adds a rarely considered dimension to the room problem.

The region contains large volumes of volcanic rocks whose time relations are not considered relevant, because they represent volcanic episodes unrelated to the Elkhorn Mountains Volcanics. The most widespread of these are the upper Eocene quartz latitic rocks of the Lowland Creek Volcanics, in the western part of the region (Smedes, 1962), which contain biotite phenocrysts that have K-Ar ages of about 50 m.y. (Smedes and Thomas, 1965). Though chemically similar to some rocks of the Elkhorn Mountains suite, they seem to represent a new volcanic episode, for there is no evidence of indigenous volcanic activity between Elkhorn Mountains time and Lowland Creek time. Excluded from consideration, too, are the Adel Mountain Volcanics of Lyons (1944) that occupy the northeast corner of the region. The Adel Mountain Volcanics of latest Cretaceous (or Paleocene?) age are younger than the Elkhorn Mountains Volcanics (Schmidt, 1963; Viele and Harris, 1965, p. 414), and are petrologically dissimilar, distinctly alkalic, and thus more closely related to rocks of the central Montana alkalic province farther east (Larsen, 1940).

## TECTONISM

The Late Cretaceous tectonic history is not as clear as the volcanic and plutonic histories, owing to lack of evidence at some crucial places and times. The key difficulties are the paucity and peripheral position of uppermost Cretaceous rocks, and the absence of Paleocene rocks. Paradoxically, this is a result of expanding knowledge. For many decades, until about 1950, most of the pyroclastic and volcaniclastic rocks of the region were assigned to the Livingston Formation of presumed latest Cretaceous and Paleocene age. In recent years, the volcanic rocks have all been reassigned to the Elkhorn Mountains Volcanics, and the volcaniclastic ones that are peripheral to the primary pile have been shown also to be entirely of Late Cretaceous age, although they are still in the Livingston Formation (Skipp and Peterson, 1965; Roberts, 1963, and 1965). In reviewing the tectonic history, we shall discuss folding and thrust faulting separately, and then explain the omission of another tectonic category — steep faulting.

**Folding.** The earliest folding, or tilting, of regional consequence slightly preceded the Elkhorn Mountains Volcanics, though local folding during deposition of the Slim Sam Formation has been reported (Smedes, 1966, p. 21, 96, 112). In the Whitehall area, halfway between Butte and Three Forks, the Elkhorn Mountains Volcanics lie on the Madison Group (Mississippian) with angular discordance of 15° to 20° (Alexander, 1955, p. 67). Minor unconformities are recorded in the Clark Fork Valley near the northwest edge of the volcanic field (Gwinn and Mutch, 1965, p. 1127-1128) and near the south edge in the Three Forks area (Robinson, 1963, Pl. 1).

In some places, however, there is no hiatus between the Slim Sam Formation and the Elkhorn Mountains Volcanics. South of Townsend (Klepper and others, 1957, p. 32) and in part of the northern Elkhorn Mountains (Smedes, 1966, p. 24), the Slim Sam Formation grades upward into the Elkhorn Mountains Volcanics. Near Wolf Creek, the equivalents of the Slim Sam Formation and Elkhorn Mountains Volcanics also are conformable (Schmidt, 1963).

The most widespread and intense regional folding came later. In the west-central part of the region, stratified rocks that are preserved on top of the batholith are in broad, shallow folds that generally trend north to north-northeast (*see,* for example, Ruppel, 1961 and 1963, Pl. 1). The folds involve mostly Elkhorn Mountains Volcanics, and they are truncated over a large area north and west of Butte by the Lowland Creek Volcanics of early Eocene age (Smedes, 1962; Smedes and Thomas, 1965), and are, therefore, late or post-Campanian and pre-early Eocene.

Much larger folds, miles broad and thousands of feet deep, characterize the northern and eastern sectors. The large folds just east of the batholith are open and upright (*see,* for example, Klepper and others, 1955, Pls. 1, 2, and 3; Robinson, 1963, Pl. 1). Farther away, east of the Missouri River, the folds tend to be tighter and less symmetrical; many are overturned to the east (*see,* for example, Mertie and others, 1951, Pl. 1, or Robinson, 1967). On the northeast flank of the Big Belt Mountains, where the Disturbed Belt (usage of Robinson, 1959) meets the Central Montana Uplift, the more easterly folds are not merely overturned, but are complexly refolded (W. B. Myers, written commun., 1966).

Just when these large folds developed can be fixed only within rather broad limits. East and southeast of the batholith, the youngest rocks involved in the folds are Elkhorn Mountains Volcanics, and northwest of Three Forks the eroded edges of the folds are overlain by rocks as old as middle or late Eocene (Robinson, 1963, Pl. 1), so here the main folding can be dated as post-middle Campanian and pre-middle Eocene.

**Thrust faulting.** A zone of thrust faults forms a broad arc along the southern and eastern margins of the region. The zone at the southern margin is narrow; in places it consists of a single north-dipping fault, the Highland–Jefferson Canyon thrust, and elsewhere it is rarely more than a few miles wide. On the eastern margin the thrust zone, here called the Sixteenmile thrust zone (Robinson, 1959), is as much as 15 miles wide. The same zone continues with north-northwesterly strike, westerly dip and greatly varying width far into Canada. In northern Montana its westernmost element is the famous Lewis thrust. Where the fault zone continues beyond the southwest corner of the batholith region is uncertain; thrusts trending both west and south are known, but their regional significance is still obscure (H. W. Smedes, oral commun., 1967).

The thrusts, like the folds, involve all the stratified rocks datable as Cretaceous. In most of the region, therefore, they are no older than middle Campanian (post-Elkhorn Mountains Volcanics); and in the northeastern sector, they are no older than late Maestrichtian (post- or intra-Adel Mountain Volcanics).

A somewhat different time range applies north of Wolf Creek, the only part of the region where Cretaceous rocks younger than the Elkhorn Mountains Volcanics are preserved. These include the St. Mary River Formation of late Campanian and Maestrichtian age and the Adel Mountain Volcanics of Lyons (1944) which are younger than at least the lower part of the St. Mary River Formation (Schmidt, 1963) and which may be contemporaneous with the upper part (Schmidt and Zubovic, 1961, p. C177), or which may be entirely younger (Viele and Harris, 1965, p. 414) and possibly Paleocene. These units are folded with the underlying Two Medicine Formation, which includes lithologic and temporal equivalents of the Elkhorn Mountains Volcanics. The eroded southern edges of some of these folds are unconformably overlain in northern Townsend Valley by lower Oligocene basin deposits (Mertie and others, 1951, Pl. 1; White, 1954). Thus, major folding in the northeast sector occurred between very late Maestrichtian or Paleocene time and early Oligocene time.

The thrusts did not form simultaneously. In the Sixteenmile zone they are younger to the west, because the more easterly thrusts (Fig. 2), such as the Maudlow thrust of the Maudlow area (Skipp and Peterson, 1965), the Moors Mountain thrust, southeast of Wolf Creek (W. B. Myers, written commun. 1966), and the Cobern Mountain thrust, north of Wolf Creek (Schmidt and Zubovic, 1961), are in places tightly folded and are successively truncated and overridden by more westerly thrusts. The westernmost thrusts, such as the Lombard thrust, near Three Forks (Robinson, 1963, Pl. 1) or the Eldorado thrust, west of Wolf Creek (Schmidt, 1963), are folded gently, or not at all. Even the youngest thrusts do not involve the Tertiary basin deposits.

So far as the field evidence goes, major thrusting began no earlier than middle Campanian time and ended before late Eocene time. Thrusting probably did not continue very long into the Paleocene, because enough time had to elapse after thrusting and before basin filling to form the basins and develop exterior eastward drainage (Robinson, 1961, p. 1010-1011).

**Steep faulting.** Steep faults are a prominent part of the regional geology. They are of two main sorts: (1) basin-and-range faults that partly bound the present main valleys and mountain ranges; and (2) block faults that are confined to areas of plutonic and volcanic rocks.

Despite their prominence, these structures receive little attention in this paper. The basin-and-range faults displace upper Tertiary and even Quaternary rocks, and are thus too young to be [illegible] been active in Late Cretaceous time too, but at present there is no way to determine this. Block faults were indeed active during Late Cretaceous time, many of them recurrently; however, even the largest block faults, such as the steep fault that marks the eastern margin of the batholith (Fig. 2), appear to have been produced by local stresses that are related to plutonic and volcanic events. The smaller ones are plainly of local origin, because they are restricted to the interior of the batholith and the volcanic edifice (*see,* for example, Ruppel, 1963, Pl. 1; Smedes, 1966, Pls. 1 and 2). Even if local control were to be debated, the block faults are so intimately involved with the volcanism and plutonism that their chronology cannot be independently determined.

## INTERRELATIONS OF VOLCANIC, PLUTONIC, AND TECTONIC EVENTS

To this point, we have tried to date volcanic, plutonic, and tectonic events independently of each other to avoid any element of circularity. This noble principle was not violated by the use of the Elkhorn Mountains Volcanics to date plutonic and tectonic events, because the formation was employed only as a stratigraphic datum; in this context its origin is irrelevant. But such treatment is highly artificial, for these events were, in fact, intimately and inextricably interrelated. When these relations are taken into account, some gaps in the history are filled, and a slightly different view emerges of the probable distribution in time of volcanism, folding, and thrusting.

The mutual relations of volcanic and plutonic rocks suggest strongly that the Elkhorn Mountains Volcanics were erupted in a somewhat different time span than direct field evidence or radiometry indicate. At issue are the several K-Ar determinations, centering around 73 m.y., on biotite and feldspar from the middle welded-tuff member. In places even the upper member is invaded by the Butte Quartz Monzonite (*see,* for example, Smedes, 1966, Pl. 1) and is clearly older than most of the batholith; indeed, in several places the upper member was folded and faulted before the batholith was emplaced (Klepper and others, 1957, Pls. 1, 2; Smedes, 1966, Pl. 1). Yet the apparent isotopic age of the welded-tuff member is a few million years less than, or at best about the same as, the K-Ar age (75-77 m.y.) of hornblende in batholithic rocks that intrude it. A reasonable conclusion is that the biotite and plagioclase of the welded tuff have lost argon, and are a little older than they seem to be, an opinion reached earlier on stratigraphic grounds.

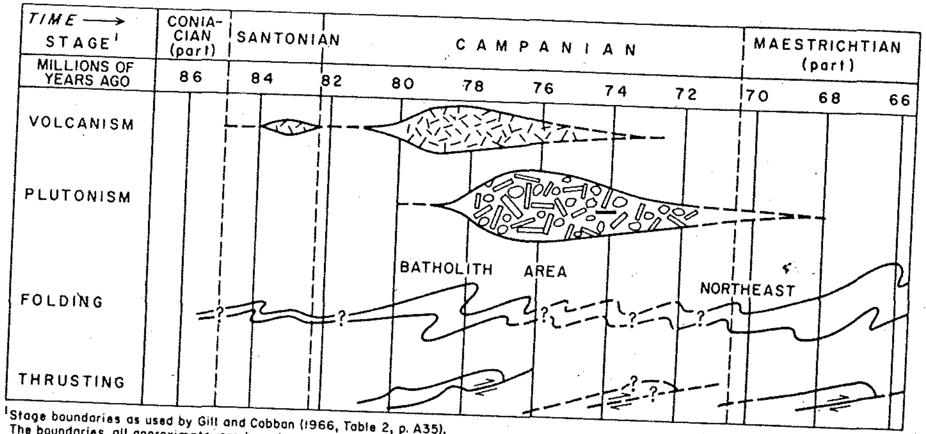
The relations between folding and plutonic rock masses demonstrate that many large folds formed before or during emplacement of the batholith and its satellites. The Butte Quartz Monzonite plainly cuts many folds. Even the youngest isotopic age from the Butte Quartz Monzonite is more than 70 m.y. (samples 10, 14, 16, and 18 on Figs. 3 and 4 represent this unit). Of the more mafic (gabbroic and dioritic) sills, some are older than folds; some may be contemporaneous. Quartz monzonitic and quartz dioritic sills in folded rocks commonly vary in thickness with changes in attitude of the enclosing strata and were apparently intruded during or slightly after folding. Unfortunately, no radiometric ages of sills are available for closer dating of both sills and penecontemporaneous folds. Nevertheless, it is clear that the main folding near the batholith ended more than 70 m.y. ago and did not continue into the Tertiary, as the field evidence would permit.

But this cannot be the whole story, for the main folding at the northeastern perimeter of the region near Wolf Creek involves rocks as young as early Maestrichtian (from 68 to 70 m.y. old), and there are no angular unconformities lower in the Cretaceous section. Consequently, main folding did not even begin at the above location until less than 70 m.y. ago. When all available evidence is considered, it appears that near the batholith the main folding occurred within Campanian time, but farther northeast, main folding did not occur until Maestrichtian time or later. Folding may have culminated in post-Campanian time at the northern and eastern margins of the region also, but this cannot be demonstrated in the absence of rocks of appropriate age.

Relations between thrusts and plutonic rocks show that thrusting began early in the tectonic history, and that thrusting and plutonic invasion overlapped. In the southwest corner of the region the Highland–Jefferson Canyon thrust is cut by the Rader Creek pluton (Fig. 3), which has yielded K-Ar ages as great as 77 m.y. Just the opposite relation prevails between satellites of the batholith and the Lombard thrust of the same fault zone in the Toston and Three Forks quadrangles (Robinson, 1963, Pl. 1; 1967). There, the Lombard thrust clearly cuts and is younger than several plutons and sills of quartz monzonite that lie in its upper plate. These plutons and sills have not been isotopically dated, but their composition suggests that they are younger than the Rader Creek pluton.

## CODA

The time relations of volcanism, plutonism, folding, and thrusting in the Boulder batholith region in Late Cretaceous time are summarized in Figure 6. With due regard for the caveats posted here and there in the foregoing text, the diagram plainly shows that all these dynamic happenings began and ended within a few million years of each other during a span of about 20 m.y. Major folding, thrusting, and volcanism started at about the same time, though not always at the same places, and a little earlier than plutonism. In any given locality, volcanism ended before major folding; the climax of plutonism followed the climax of volcanism; folding preceded and accompanied plutonism near the batholith, but followed plutonism farther away; thrusting continued a while after folding ceased. Given so close a temporal and spatial association of volcanism, plutonism, and tectonism, it is inconceivable that a genetic relation does not also exist among these phenomena. Its nature, however, is beyond the scope of this paper. A review of the literature bearing on the matter, and a provocative, if not wholly convincing, new interpretation has recently been offered by Hamilton and Myers (1967).



¹Stage boundaries as used by Gill and Cobban (1966, Table 2, p. A35). The boundaries, all approximate, are based on ammonite faunal zones.

Figure 6. Time relations of Late Cretaceous volcanism, plutonism, folding, and thrusting in the Boulder batholith region.

The gloriously mixed-up relations in the Boulder batholith region should give pause to certain theorists or generalizers. For example, many workers — especially those who believe that all batholiths are regurgitated sediments — assume there is no significant relation between surface effusion and subsurface invasion. Other workers assume a reciprocal relation between surface effusion and subsurface invasion. Neither can take comfort from the information presented here.

To return to our starting point, the Boulder batholith, though assuredly magmatic, is unmistakably synorogenic, as Stille (1940, p. 264) inferred; therefore, while Gilluly (1965, p. 24) is correct in stating that "the great Cretaceous thrusts of Montana . . . seem clearly to be décollement structures" he is not correct in maintaining, in the same paragraph, that this orogeny was "essentially without plutonic associations." To question his regional interpretation is not to take issue, as Platt (1966) has done, with Gilluly's (1965, p. 3) broad generalization that "orogeny and plutonism are far from synonyms in geologic history," but only to show that one of his examples was infelicitous.

## REFERENCES CITED

**Alexander, R. G., Jr.**, 1955, The geology of the Whitehall area, Montana: Yellowstone-Bighorn Research Assoc., Contr. 195, 111 p.

**Billingsley, Paul, and Grimes, J. A.**, 1916, Ore deposits of the Boulder batholith of Montana: Am. Inst. Min. Eng. Trans., v. 51, p. 31–47.

——— 1918, Ore deposits of the Boulder batholith of Montana: Am. Inst. Min. Eng. Trans., v. 58, p. 284–368.

**Eardley, A. J.**, 1962, Structural geology of North America (2d edition): New York, Harper and Row, 754 p.

**Gill, J. R. and Cobban, W. A.**, 1966, The Red Bird section of the Upper Cretaceous Pierre Shale in Wyoming: U.S. Geol. Survey Prof. Paper 393-A, 73 p.

**Giletti, B. J.**, 1966, Isotopic ages from southwestern Montana: Jour. Geophys. Research, v. 71, no. 16, p. 4029–4036.

**Gilluly, James**, 1965, Volcanism, tectonism, and plutonism in the western United States: Geol. Soc. America Spec. Paper 80, 69 p.

**Gwinn, V. E., and Mutch, T. A.**, 1965, Intertongued Upper Cretaceous volcanic and nonvolcanic rocks, central-western Montana: Geol. Soc. America Bull., v. 76, no. 10, p. 1125–1144.

**Hamilton, Warren, and Myers, W. B.**, 1967, The nature of batholiths: U.S. Geol. Survey Prof. Paper 554-C, 30 p.

**Hart, S. R.**, 1964, The petrology and isotope-mineral age relations of a contact zone in the Front Range, Colorado: Jour. Geology, v. 72, no. 5, p. 493–525.

**Klepper, M. R., Weeks, R. A., and Ruppel, E. T.**, 1957, Geology of the southern Elkhorn Mountains, Jefferson and Broadwater Counties, Montana: U.S. Geol. Survey Prof. Paper 292, 82 p.

**Knopf, Adolph**, 1957, The Boulder bathylith of Montana: Am. Jour. Sci., v. 255, no. 2, p. 81–103.

——— 1964, Time required to emplace the Boulder bathylith, Montana: a first approximation: Am. Jour. Sci., v. 262, no. 6, p. 1207–1211.

**Larsen, E. S.**, 1940, Petrographic province of central Montana: Geol. Soc. America Bull., v. 51, no. 6, p. 887–948.

**Lyons, J. B.**, 1944, Igneous rocks of the northern Big Belt Range, Montana: Geol. Soc. America Bull., v. 55, p. 445–472.

**Mertie, J. B., Jr., Fischer, R. P., and Hobbs, S. W.**, 1951, Geology of the Canyon Ferry quadrangle, Montana: U.S. Geol. Survey Bull. 972, 97 p.

**Obradovich, J. D., Peterman, Z. E., and Mudge, M. R.**, 1967, Rb-Sr and K-Ar ages of Precambrian Belt rocks, Sun River area, Montana, *in* Abstracts for 1966: Geol. Soc. America Spec. Paper 101, p. 413–414.

**Pardee, J. T., and Schrader, F. C.**, 1933, Metalliferous deposits of the Greater Helena mining region, Montana: U.S. Geol. Survey Bull. 842, 318 p.

**Platt, L. B.**, 1966, Orogeny and geochronology: Am. Jour. Sci., v. 264, no. 6, p. 745–750.

**Roberts, A. E.**, 1963, The Livingston Group of south-central Montana, *in* Short papers in geology and hydrology: U.S. Geol. Survey Prof. Paper 475-B, p. B86–B92.

——— 1965, Correlation of Cretaceous and lower Tertiary rocks near Livingston, Montana, with those in other areas of Montana and Wyoming: U.S. Geol. Survey Prof. Paper 525-B, p. B54–B63.

**Robinson, G. D.,** 1959, The Disturbed Belt in the Sixteenmile area, Montana: Billings Geol. Soc., 10th Ann. Field Conf. Guidebook, p. 34–40.

——— 1961, Origin and development of the Three Forks Basin, Montana: Geol. Soc. America Bull., v. 72, p. 1003–1014.

——— 1963, Geology of the Three Forks quadrangle, Montana: U.S. Geol. Survey Prof. Paper 370, 143 p.

——— 1967, Geologic map of the Toston quadrangle, southwestern Montana: U.S. Geol. Survey Misc. Geol. Inv. Map I-486.

**Robinson, G. D., and Marvin, R. F.,** 1967, Upper Cretaceous volcanic glass from western Montana: Geol. Soc. America Bull., v. 78, p. 601–608.

**Ruppel, E. T.,** 1961, Reconnaissance geologic map of the Deer Lodge quadrangle, Powell, Deer Lodge and Jefferson Counties, Montana: U.S. Geol. Survey Mineral Inv. Field Studies Map MF-174.

——— 1963, Geology of the Basin quadrangle, Jefferson, Lewis and Clark, and Powell Counties, Montana: U.S. Geol. Survey Bull. 1151.

**Schmidt, R. G.,** 1963, Preliminary geologic map and sections of the Hogan 4 Southeast quadrangle, Lewis and Clark County, Montana: U.S. Geol. Survey Misc. Geol. Inv. Map I-379.

——— 1966, Preliminary geologic map of the Comb Rock quadrangle, Lewis and Clark County, Montana: U.S. Geol. Survey Misc. Geol. Inv. Map. I-468.

**Schmidt, R. G., and Zubovic, Peter,** 1961, Cobern Mountain overthrust, Lewis and Clark County, Montana, *in* Short papers in the geologic and hydrologic sciences: U.S. Geol. Survey Prof. Paper 424-C, p. C175–C177.

**Skipp, Betty, and Peterson, A. D.,** 1965, Geologic map and cross sections of the Maudlow quadrangle, southwestern Montana: U.S. Geol. Survey Misc. Geol. Inv. Map I-452.

**Slaughter, Maynard, and Earley, J. W.,** 1965, Mineralogy and geological significance of the Mowry bentonites, Wyoming: Geol. Soc. America Spec. Paper 83, 116 p.

**Smedes, H. W.,** 1962, Lowland Creek Volcanics, an upper Oligocene formation near Butte, Montana; Jour. Geol., v. 70, no. 3, p. 255–266.

——— 1966, Geology and igneous petrology of the northern Elkhorn Mountains, Jefferson and Broadwater Counties, Montana: U.S. Geol. Survey Prof. Paper 510, 116 p.

**Smedes, H. W., and Thomas, H. H.,** 1965, Reassignment of the Lowland Creek Volcanics to Eocene age: Jour. Geol., v. 73, no. 3, p. 508–510.

**Stille, Hans,** 1940, Einführung in den Bau Amerikas: Berlin, Gebrüder Borntraeger, 717 p.

**Tilling, R. I., Klepper, M. R., and Obradovich, J. D.,** in press, K-Ar ages and time span of emplacement of the Boulder batholith, Montana: Am. Jour. Sci.

**Veile, G. W., and Harris, F. G., III,** 1965, Montana Group stratigraphy, Lewis and Clark County, Montana: Am. Assoc. Petroleum Geologists Bull., v. 49, no. 4, p. 379–417.

**White, T. E.,** 1954, Preliminary analysis of the fossil vertebrates of the Canyon Ferry Reservoir area [Mont.]: U.S. Natl. Mus. Proc., v. 103, no. 3326, p. 395–438.

PUBLICATION AUTHORIZED BY THE DIRECTOR, U.S. GEOLOGICAL SURVEY, WASHINGTON, D.C.

---

# Cenozoic Volcanism and Sedimentation, Silver Peak Region, Western Nevada and Adjacent California

PAUL T. ROBINSON

*Department of Geology, Oregon State University,*
*Corvallis, Oregon*

EDWIN H. MCKEE

*U.S. Geological Survey,*
*Menlo Park, California*

RICHARD J. MOIOLA

*Field Research Laboratory, Mobil Oil Corporation,*
*Dallas, Texas*

## ABSTRACT

Cenozoic deposits of the Silver Peak region, western Nevada, and adjacent California consist principally of continental sedimentary and pyroclastic rocks of the Esmeralda Formation and lavas and tuffs of the Silver Peak volcanic center.

The sedimentary rocks comprise several thick sequences of tuffaceous volcanic sandstone and siltstone and interbedded air-fall tuff. These rocks were deposited in basins that coincide in a general way with the present valleys. Thick wedges of conglomerate and sandstone occur along the basin margins and reflect source areas.

Most of the sedimentary rocks were deposited under fluctuating fluviatile and lacustrine conditions, but paludal conditions prevailed locally. Abrupt facies changes and numerous local unconformities indicate that deposition was not uniform within a given basin.

The sedimentary rocks range in age from late Miocene to late Pliocene. The oldest reliably dated rocks in the Esmeralda Formation are 13.1 m.y.