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n the Nature of the Boulder Batholith of Montana

TRACT

a recent review of the nature of batholiths, lton and Myers (1967) interpreted the er batholith of western Montana to be ect a gigantic mantled lava flow . . . . only kilometers thick," that flowed, under a t its own ejecta, across a broad structural Such an interpretation is inconsistent abundant geologic and geophysical data. main mass of the batholith, the Butte z Monzonite, does not have the character- of a lava flow or a laterally emplaced Its volcanic cover was not a floating cap a laterally stable roof that was part of a nic plateau which occupied at least twice ea of the batholith. It does not thin toward dges but is generally steep sided. Its flow tures are predominantly steep rather than horizontal. It is separated from two smaller ng plutons by thin vertical septa kilome- long. Its emplacement required more than , a rate orders of magnitude too slow for le sheet only a few kilometers thick, how- extensive.

he batholith is more than a few kilometers k. Recent gravity studies (Burfeind, 1967; mi, 1969) suggest a maximum thickness of 5 km to their authors, but the calculations based on (1) assumed lateral and vertical geneity of the batholith, whereas in real- e Butte Quartz Monzonite core is discon- usly rimmed by more mafic, denser ons; and (2) inappropriate densities, lead- o excessive apparent density contrasts. The ty data suggest to us that the batholith is than 15 km thick. Heat flow, cooling rate, seismic data also are compatible with a ness of at least 15 km, but are difficult to cile with a thickness of only a few kilome-

onvincing examples of extrusive or quasi- sive thin batholiths must be sought else- e.

INTRODUCTION

In 1967, Warren Hamilton and W. Bradley Myers took a new look at an old subject, the nature of batholiths. They wrote that batholithic magmas originated by partial melting deep in the crust or in the upper mantle and penetrated upward by zone melting and assimilation, ultimately to spread out as broad sheets near the surface or, more often, to reach the surface and crystallize beneath a mantle of their own ejecta. Their conclusion was that batholiths are thin, rootless, and genetically unrelated to metamorphic processes in the usual sense, and differences in their forms and settings merely reflect differing levels of exposure. If this is truly the nature of batholiths, some classic puzzles, such as the room problem and magma versus migma, are solved and some difficult new ones arise. The very name "batholith" becomes a misnomer.

Hamilton and Myers (1967) use the Boulder batholith of western Montana (Fig. 1) as one of their chief examples. Among American batholiths this is a good choice, for the Boulder batholith is widely exposed, yet retains large remnants of its original cover, and both the batholith and its regional setting are well studied. If *Batholithus americanus* is a valid species, the Boulder batholith is an appropriate holotype.

Relying primarily on the geologic mapping of Knopf (1963) and Ruppel (1963) along the north and northwest margins of the batholith, and on reconnaissance gravity observations by Renick (1965) near the north edge, Hamilton and Myers (1967, p. C7-C9) conclude that "the batholith magma flowed, in effect a gigantic mantled lava flow, across a broad basin. . ." The mantle was "a crust of volcanic rocks perhaps 2 km thick [that] floated upon granitic magma over a region of about 7,000 square kilometers" and the batholith itself was no more than 5 km thick.

al Society of America Bulletin, v. 82, p. 1563-1580, 9 figs., June 1971

The model thus conjured is one of grandeur and simplicity, and is likely to have broad appeal, yet the model is not at all convincing when examined closely. We hope to show that Knopf's mapping and Renick's gravity measurements are amenable to quite different interpretation, and that key geological and geophysical evidence from the rest of the bat olith is incompatible with thin sheet-like for and emplacement by lateral flowage. It is n our purpose to debate the general batholi question.

We begin by outlining the field relations o the batholith. More thorough discussions ar ven by Robinson and others (1968), and by Knopf (1957).

FIELD RELATIONS

As now exposed, most of the batholith and its ellites, identified on Figure 1 as "Upper etaceous plutonic rocks," intrude layered ks unmetamorphosed except by the batholith itself: upper Precambrian, Paleozoic, an Mesozoic marine sedimentary rocks of shelf c miogeosynclinal facies, more than 6 km thick Mesozoic continental sedimentary rocks nearl 1 km thick; and Upper Cretaceous calc-alkali volcanic rocks, the Elkhorn Mountains Volcanics, more than 4 km thick. A major pluton at th south end of the batholith also cuts regionall metamorphosed Precambrian rocks. The sedimentary rocks are confined to the flanks of th batholith, except for a few small roof pendant in the western part, about halfway between Deer Lodge and Butte. Large remnants of Elkhorn Mountains Volcanics are preserved atop the northwestern and north-central parts of the batholith. The eastern margin of the main batholithic mass is straight for long distances across rugged terrain, and therefore steep; the north and south margins are irregular but generally steep; the west flank is masked by younger rocks and its dip is unknown. The intrusions cut cleanly across and have thermally metamorphosed country rocks of the most varied lithology. Many intrusive contacts with hornfelsed roof rocks are subhorizontal in overall aspect, but highly variable in detail.

The batholith is in a broad structural sag in folded upper Precambrian, Paleozoic, and Mesozoic rocks; to the east and north, the country rocks are progressively more tightly folded, then overturned, and finally overthrust eastward and northeastward (only the main thrusts and fold axes are shown on Fig. 1). The southernmost part of the batholith, as now exposed, intrudes lower Precambrian metamorphic rocks, as does the small contemporaneous (Giletti, 1966, p. 4035) Tobacco Root batholith (Smith, 1965) to the southeast (shown at the south-central edge of Fig. 1). The metamorphic rocks, of unknown thickness, are largely light-colored paragneiss and schist, rich in quartz, plagioclase, and biotite; marble and amphibolite are conspicuous but less abundant components. Similar metamorphic rocks probably underlie the sedimentary rocks to the north. Tertiary volcanic rocks and Cenozoic basin deposits unconformably overlie much of the batholith, concealing many relationships, especially on the west flank.

A closer view of the Boulder batholith (Fig. 2) shows it to be a composite mass, exposed over more than 6,000 km², comprising at least a dozen plutons. The plutons range from syenogabbro to alaskite, but most of them are quartz monzonite and granodiorite. Contacts between the plutons tend to be sharp and steep. The

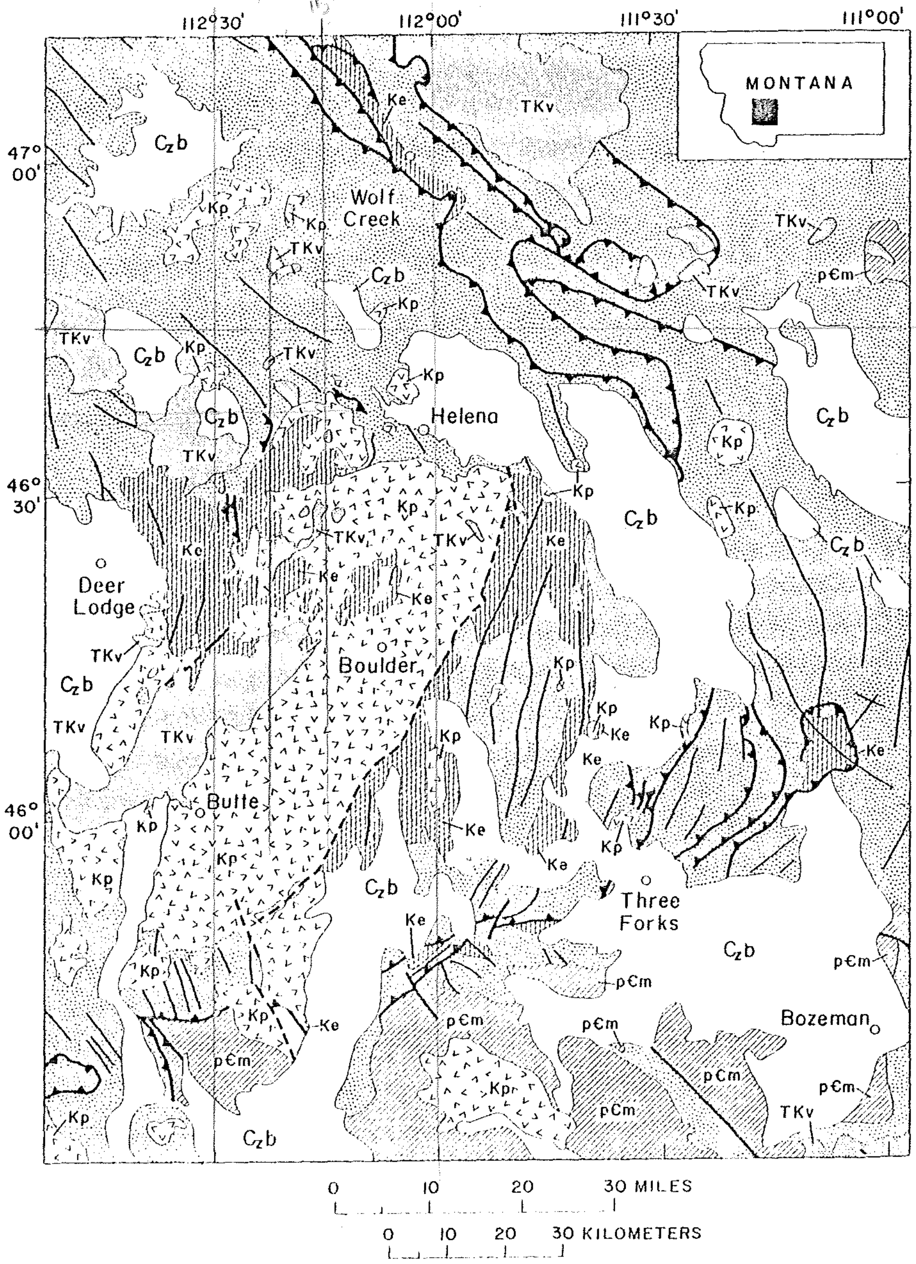


Figure 1. Regional setting of the Boulder batholith (slightly modified *from* Robinson and others, 1968, Fig. 2

main body, the Butte Quartz Monzonite, cuts smaller, somewhat less silicic plutons and a few mafic plutons; in turn, it is cut by smaller, somewhat more silicic plutons (Tilling and others, 1968; Knopf, 1957, p. 90-95; Smedes, 1966, p. 58-59). Field evidence that the plutons wer intruded in general order of increasing silic content is supported by about 40 K-Ar ag determinations (Tilling and others, 1968, Fi 2; Robinson and others, 1968, Fig. 4), sampl

calities for which are shown on Figure 2 and resented graphically on Figure 3. These determinations further indicate that the entire bath- lithic complex was emplaced within about 10 y. The plutons are ordered in space as well in time: those more mafic than Butte Quartz Monzonite—chiefly granodiorite, but including gabbro, syenogabbro, syenodiorite, monzonite—discontinuously flank the B Quartz Monzonite on the north, south, east; plutons more silicic than Butte Qu Monzonite—subsumed on Figure 2 as "le cratic rocks"—are mainly south of the B Quartz Monzonite mass; and the more s

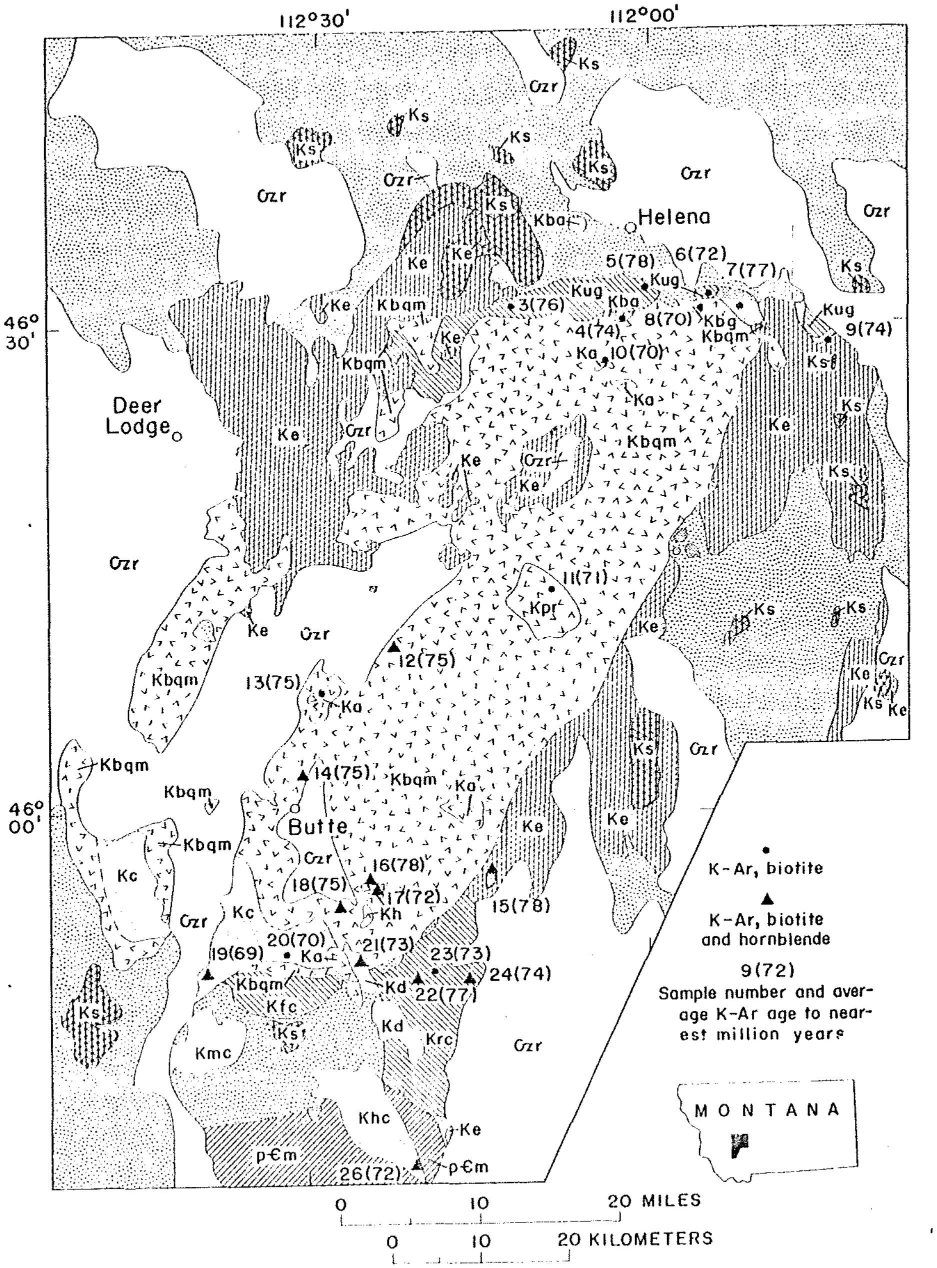
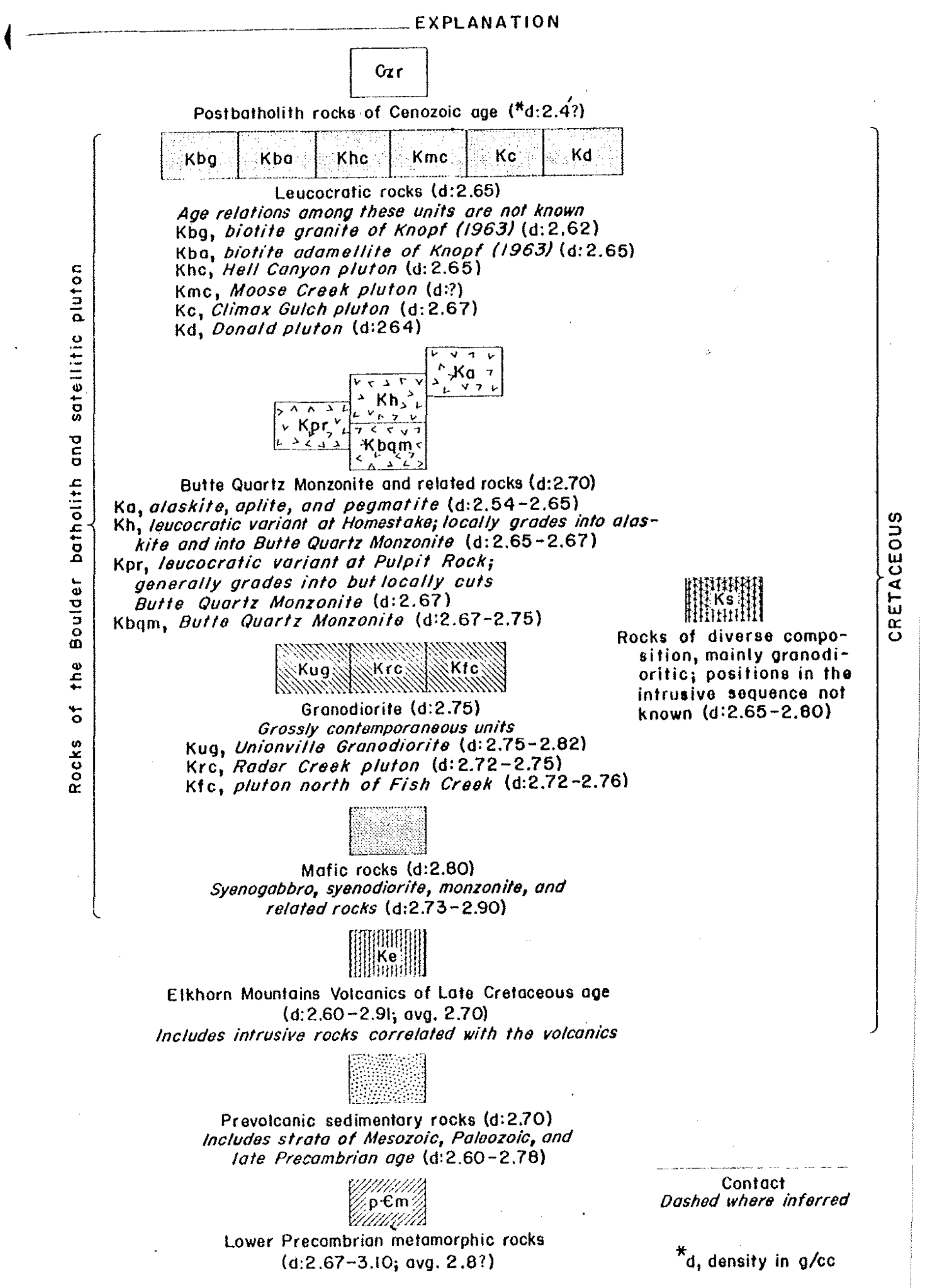


Figure 2. Geologic map of the Boulder batholith and vicinity showing location and age of rocks dated by K-Ar method (slightly modified *from* Tilling and others, 1968, Fig. 1), and rock density data (*see* Tables 1 and 2 sources).



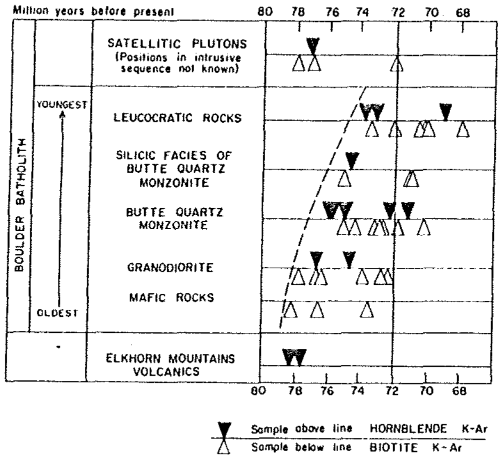


Figure 3. K-Ar ages of minerals from the Boulder batholith and the Elkhorn Mountains Volcanics. Ages of batholith minerals are grouped according to the map units of Figure 2 and arranged in known or inferred intrusive sequence (slightly modified from Tilling and others, 1968, Fig. 2).

variants of Butte Quartz Monzonite itself occur within the mass.

IS THE BOULDER BATHOLITH A MANTLED LAVA FLOW?

Many geologists have worked in the Boulder batholith region since Lindgren (1886) first described "granite" at Mullan Pass, in the north end of the batholith, but few have ventured to interpret in any detail its configuration at depth or its manner of emplacement. The earliest worker, Weed (1901, p. 452), inferred that the granite rose to within a thousand feet of the surface and "must have either penetrated between the andesites (= Elkhorn Mountains Volcanics) and the base upon which they rested or removed the basal rocks, whatever they were." Lawson (1914) took a similar position by concluding that the "batholith" is a laccolith, intruded between the volcanic rocks and older rocks. This interpretation was conceded by Knopf (1914, p. 396-397) to be a "working hypothesis . . . entitled to much weight," but it was vigorously assailed by Billingsley (1916, p. 32) and thereafter has been largely ignored. Billingsley's own view, based largely on outcrop patterns, was that the batholith is a transgressive dome-shaped mass that widens at depth and extends indefinitely downward, presumably to the base of the crust. Grout and Balk (1934, p. 889), using the structural methods of Hans Cloos, reasoned that the "mass must have risen steeply from considerable depths. It is a batholith in almost every sense of the word—a large plutonic igneous rock, with wide direct connection with great depths—rather than a narrow feeding channel." Knopf, the most devoted student of the batholith, has little to say about the batholith below its present level of visibility. In his final interpretive statement (1957, p. 88), he said, ". . . the intrusive magma manifestly made room for itself by crowding aside the enveloping rocks." Now Hamilton and Myers (1967, p. C7) envision the batholith as "an extrusive complex . . . in effect a gigantic mantled lava flow, across a broad basin . . ."

If this is so, it should be possible to show that the batholithic flow was a sheet that extended itself laterally and was emplaced quickly. To us this is unthinkable for most of the plutons of the batholith, and Hamilton and Myers do not assert otherwise (1967, p. C9); the lava flow they visualize is plainly the Butte Quartz Monzonite (although on p. C9 they ascribe separate flow origins to other smaller bodies in the west-central and north marginal parts of the batholith). It might be argued that if cogenetic plutons both slightly older and slightly younger than the Butte Quartz Monzonite are undeniably intrusive, and at the same level of exposure, the Butte Quartz Monzonite could scarcely be otherwise, but we will not pursue this point.

Did its Volcanic Cover Float Laterally?

The outcrop pattern of the Butte Quartz Monzonite could indeed be that of a subhorizontal sheet and its roof remnants may conceivably represent an original floating crust, for the remnants are almost wholly of Elkhorn Mountains Volcanics, rocks similar in chemical composition and geologic age to the underlying quartz monzonite.

But the roof remnants *are* merely remnants. When they are viewed in context with the original volcanic field of which they were a part, it is clear that they never constituted a laterally floating crust, as would be required "if the batholith magma flowed, in effect a gigantic mantled lava flow, across a broad basin" (Hamilton and Myers, 1967, p. C7). Three members have been mapped in the Elkhorn Mountains Volcanics, each initially more than a kilometer thick (Klepper and others, 1957, p. 31-35). The lower member, mainly autoclastic breccia and lava, and the middle member, dominantly welded tuff, are essentially coextensive; remnants of both are preserved in depositional contact on prebatholith rocks many kilometers beyond the batholith margins in all directions, over an area larger than 15,000 km², and more than twice as large as that of the batholith; the volcanic field must have been even more extensive when the batholith was emplaced (Fig. 4).

Hamilton and Myers (1967, p. C7) recognize this fact: "thick volcanic rocks formed across the entire basin before much magma spread laterally between volcanics and flow," and again (p. C22) "crust and batholith thickened simultaneously, although the volcanic rocks spread far beyond the batholith." We are in agreement, therefore, that the widespread volcanic cover could not have been a laterally floating crust, but rather formed a relatively stable roof more than 2 km thick beneath which the magma advanced. It is plain, then, that

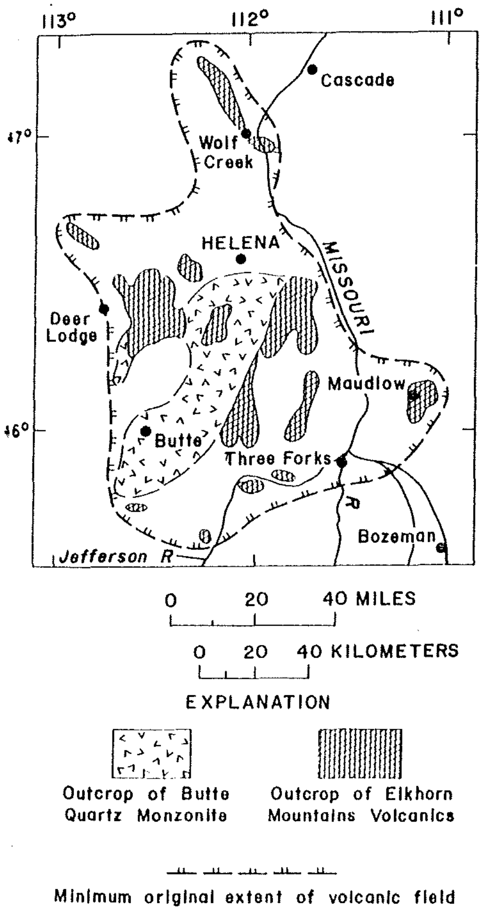


Figure 4. Comparison of areas of Boulder batholith and Elkhorn Mountains volcanic field.

Hamilton and Myers really look on the m
batholith mass, the Butte Quartz Monzonite
a thin shallow intrusive sheet.

Is Its Form Sheet-like?

As Hamilton and Myers (1967) point o
preserved roof contacts in the northweste
part of the batholith, east of Deer Lodge,
indeed indicate a gently rolling upper surfa
quasi-conformable with gently folded rocks
the lower and middle members of the volcan
(Ruppel, 1961; 1963, p. 37). But most of t
roof elsewhere is eroded or covered
younger rocks, and its former shape is mo
Furthermore, in the large roof remnant
tween Helena and Boulder (Fig. 1), only 10
east of the area mapped by Ruppel (referred
above), Butte Quartz Monzonite penetra
transgressively almost to the top of the volca
pile (Becraft and others, 1963, p. 6, Pl.
These varying roof relations were noted lo
before by Grout and Balk (1934, p. 878-87

Other border relations of the batholith p
vide even weaker evidence of over-all she
like form. Thus, Knopf's map (1963) of t
northern part of the batholith shows seve
masses of granitic rocks of varying compositi
elongated roughly parallel to trends in the adj
cent country rocks, which dip toward the ba
olith. This suggests not merely one sheet b
several to Hamilton and Myers (1967, p. C
C9), who generalize part of Knopf's map
their Figure 3, which is reproduced he
slightly modified, as our Figure 5. As Hamilt
and Myers (1967, p. C7) state: "dips in t
wallrocks tend to steepen toward the conta
with the batholith"; locally, they are even ove
turned near the contact. They attribute t
steeper marginal dips to sagging under succ
sive flows of magma and assume a batholi
floor dipping gently to the south. To Kno
(1957, p. 88) the steepened dips suggest
forceful intrusion of plutonic rocks. We agre
and further infer that the contact, steep near t
surface, probably flattens at shallow depth a
dips northward because the local aureole
thermal metamorphism is the widest and m
intense in the region and numerous large a
small satellitic plutons crop out nearby to t
north.

An aeromagnetic survey (Davis and othe
1963) shows a very steep gradient, involvi
about 1,000 gammas, just east of the area
Knopf's map, indicating "that the conceal
northern face of the batholith is nearly vertica
(p. 4). Near-surface steep contacts betwe

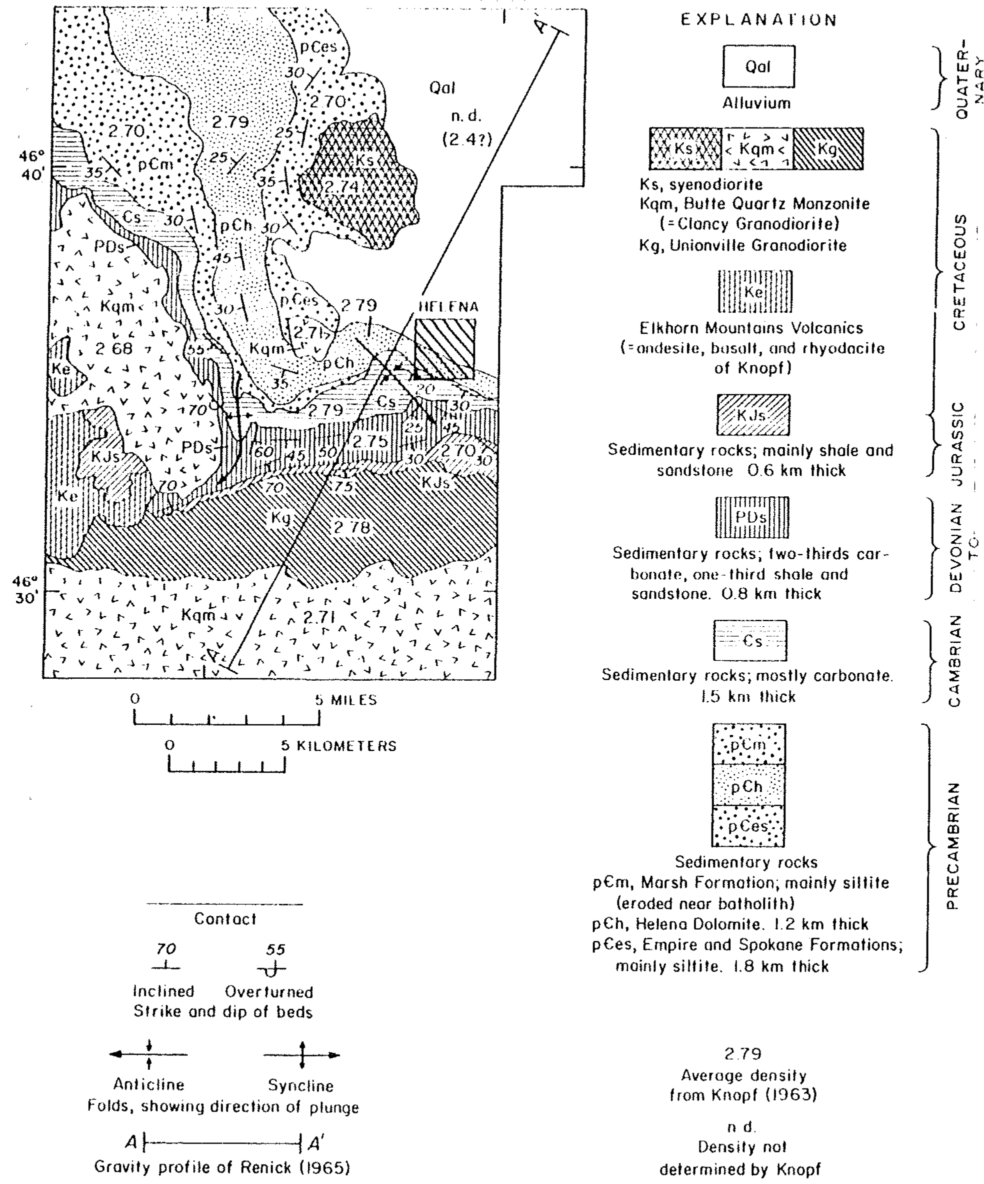


Figure 5. Geologic map of north end of Boulder batholith (slightly modified *from* Hamilton and Myers, 1967, Fig. 3, which is modified *from* Knopf, 1963), showing average rock densities.

batholith and country rocks are also the rule in the adjacent northern Elkhorn Mountains (Smedes, 1966, p. 63-64, Pl. 1).

Also cited by Hamilton and Myers (1967, p. C9) as evidence of a shallow floor is a reconnaissance gravity survey by Renick (1965), which indicates no abrupt change in the gravity field due to the granitic mass. Renick's single gravity profile (his Fig. 3) is reproduced here as Figure 6; its location is shown on Figure 5. The inferred batholith floor slopes gently south (although still too steeply for Hamilton and Myers, 1967, p. C9), but the model is not acceptable, because it is based on unrealistic choices of rock density (Fig. 6b): 2.89 g/cc for country rocks, 2.67 g/cc for batholith. Knopf (1963) systematically measured the density of hundreds of samples of igneous and sedimentary rocks there. The averages he reported, plus many additional measurements by M. R. Klepper and associates, and weighted averages based on formation thickness, are given in Table 1 and generalized in Figure 5. Knopf's measurements indicate that in this vicinity the average density of the country rocks is much lower than Renick assumed, near 2.75 g/cc, and that of batholith rocks is much higher, and is also near 2.75. Further, on the line of Renick's profile a thick sequence of Cambrian rocks (Є*s*), mainly carbonate, and Precambrian Helena Dolomite (*p*Є*h*), both of average density about 2.79, are near Upper Cretaceous Cretaceous Unionville Granodiorite (Kg), density 2.78. Given little density contrast between batholith border and country rocks here, no marked gravity change is to be expected at their contact, whatever its dip (shown by Renick, 1965, Fig. 3b, as northward near the surface, away from the batholith). The anomalous observed profile more likely reflects the relatively large density contrast between Butte Quartz Monzonite, 2.71, and adjoining Unionville Granodiorite, 2.78, and there is no reason to assume that the shape of this contact is indicative of the shape of the gross contact between batholith and country rocks. Other gravity investigators (Burfeind, 1967, p. 27, and section K-K', Pl. 3; Bonini, 1969, section A-A' on Figs. 2 and 4) suggest that the north margin is much steeper than on Renick's model (45° SW. on Burfeind's profile and steeply north on Bonini's) and extends somewhat deeper, 9 to no more than 15 km. If the models of Burfeind and Bonini have any validity, they oppose the notion that the north margin of the batholith represents the thin edge of one or more flows or thin sheets. Unfortunately, these models also are somewhat marred by unrealistic choices of densities (Table 2), as well as by selection of an over-simple batholith model, discussed later.

The east and south batholith margins consistently are steep and transgressive wherever exposed (*see* Smedes, 1966, p. 98-99; and Klepper and others, 1957, for the east margin; and Smedes, 1967, for the south margin). Such margins, whatever their origin, do not support the lateral sheet-flow hypothesis.

The west margin, as noted previously, is covered, and its nature can only be inferred. Available geophysical evidence is discussed later.

Important information on the shape of the Butte Quartz Monzonite is supplied by its contacts with other plutons. Such contacts invariably are steep. Especially significant in the present context are near-vertical screens, or septa, kilometers long, of thermally metamorphosed country rocks at plutonic contacts. One of these separates the main mass of the Butte Quartz Monzonite from a lobe of the same unit in the northern Elkhorn Mountains (Smedes, 1966, p. 85, Pl. 1); others lie between the Butte Quartz Monzonite and the older Rader

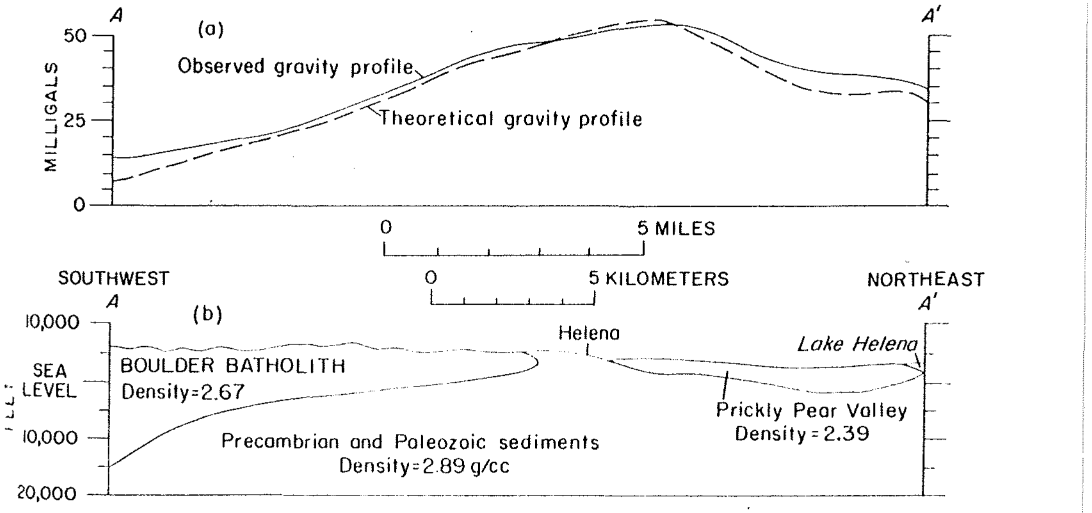


Figure 6. Gravity profile across north margin of Boulder batholith (*from* Renick, 1965, Fig. 3).

TABLE 1. ROCK DENSITIES—BOULDER BATHOLITH AREA

A. Rocks of Boulder batholith and major satellites

	Range of measured densities (g/cc)	Percent of batholith surface	Weighted average density (based on surface distribution) (g/cc)
North end of batholith[1]			
Unionville Granodiorite	2.75-2.82	..	2.78
Clancy Granodiorite (= Butte Quartz Monzonite)	2.67-2.75	..	2.71
Porphyritic granodiorite	2.65-2.71	..	2.70
Others[2]	2.61-2.84	..	2.68
Entire batholith[3]			
Plutons of leucocratic rocks (Donald, Hell Canyon, etc.)	2.58-2.67	7	2.64
Butte Quartz Monzonite	2.66-2.75	82	2.70
Alaskite and aplite ± 5%	2.54-2.65		
Granodiorite plutons (Unionville, Rader Creek, etc.)	2.65-2.82	10	2.75
Mafic rocks	2.73-2.90	1	2.80
Weighted average, entire batholith			2.70

B. Prebatholith rocks

	Range of measured densities (g/cc)	Average regional thickness (km)	Weighted average density (based on thickness) (g/cc)
Elkhorn Mountains Volcanics[1]	2.65-2.91	3.0	2.70
Paleozoic and Mesozoic sedimentary rocks (60% limestone and dolomite, 20% sandstone and siltstone, 20% shale)[4]	2.63-2.84	1.5	2.74
Upper Precambrian sedimentary rocks (30% limestone and dolomite, 40% sandstone and siltstone, 30% argillite)[4]	2.58-2.83	4.5	2.74
Weighted average, entire stratified section			2.74

[1] Density data *from* Knopf (1963).

[2] Mainly granodiorite (Knopf, 1963, p. 7).

[3] Includes Knopf's data and more than 300 measurements by Klepper and associates.

[4] Data mainly *from* Knopf (1963) supplemented by measurements by Klepper and associates.

*See also Figure 2.

TABLE 2. AVERAGE ROCK DENSITIES (IN G/CC) USED BY VARIOUS AUTHORS

	Burfeind (1967, p. 17-18)	Bonini (1969, Fig. 5)	Renick (1965, Fig. 3)	This paper
Cenozoic basin deposits	2.25	..	2.39	2.4(?)
Boulder batholith	2.67	2.66	2.67	2.70[1]
Cretaceous and Tertiary volcanic rocks	2.72	2.68	..	2.74[1]
Precambrian, Paleozoic, and Mesozoic sedimentary rocks	2.70		2.89	
Lower Precambrian metamorphic rocks	2.85	2.86	..	2.80[2]

[1] *From* Table 1.

[2] *From* Davis and others, (1965, text p. 2).

Creek pluton (Fig. 7). We are unable to visualize any process that would yield screens of this sort at the edge of a laterally emplaced sheet, whether the igneous mass on the other side is older or younger.

If the batholith, 50 km broad, is in fact a thin sheet, its lower surface should not be many kilometers down. Hamilton and Myers in their Figure 4 (1967) visualize no more than 5 km, but the depth must be two or three times greater if the previously cited gravity calculations of Burfeind or Bonini are accepted.

We think that a case can be made for a batholith floor at a depth even greater than 15 km, by making assumptions about density contrasts based on more data than were available to Burfeind or Bonini, and by taking account of the fact that the batholith is not a homogeneous body. Burfeind (1967, p. 17-18) uses a density contrast of 0.03 g/cc between batholith and stratified wall rock, based on assumed average densities of 2.67 (batholith) and 2.70 (wall rock), to explain the near-surface gravity contrast. Calculations for deeper parts employ a contrast of 0.18 g/cc between batholith and average Precambrian metamorphic (="basement") rocks, assigned a density of 2.85. Use of such a large contrast leads inevitably to the interpretation that the batholith has a shallow bottom.

We would not dispute the 0.03 near-surface density contrast, although the individual densities assumed for batholith and sedimentary wall rock are lower than available measurements indicate (*see* Tables 1 and 2), but the density assigned to the metamorphic basement seems too great, and the contrast between basement and batholith even more so.

Bonini (1969, p. 10 *and* Fig. 5) made assumptions similar to Burfeind's. His (Fig. 5, Case D) preferred figure for basement density, 2.86 g/cc, is based mainly on interpretation of regional seismic refraction data. He offers configurations based on contrasts of 0.10, 0.15, and 0.20 g/cc, but prefers a contrast between 0.15 and 0.20. A distinctly lower basement rock density—2.80 g/cc—was estimated by Davis and others (1965, text p. 2) for the adjoining Three Forks Basin. This lower density is not unreasonable, to judge from seismic refraction measurements in this region by Steinhart and Meyer (1961, p. 339) who (p. 341) recognized a crustal layer between depths of 2.5 and 22 km that has a velocity of 5.95 km/sec. The average density for this velocity is about 2.80 g/cc, according to Woollard (1959, Fig. 7), and about 2.70, according to Nafe and Drake (1968, Fig. 7). By using a basement density of 2.80, rather than 2.85 or 2.86, and a batholith density of 2.70, rather than 2.66 or 2.67, the density contrast is cut in half and the calculated depth is proportionately increased. And if the basement density figure of Nafe and Drake is used, the contrast disappears entirely!

Unfortunately, the basement-rock densities of Davis and others (1965) are scarcely more convincing than those of Burfeind (1967) or Bonini (1969), for they are not based on detailed mapping, and thus are not weighted for volume, but at least they suggest that a batholith bottom deeper than 15 km is compatible with available data.

Essential to the interpretations of both Burfeind and Bonini is lateral homogeneity in the batholith. As Burfeind (1967, p. 29) says: "If it were to be shown that there is a large increase in the density of batholithic rocks near the margins of the intrusive, then the proposed models . . . do not give a true picture of the batholith." An increase in density for parts of the batholith margin is clearly indicated on Figure 2, which is based on recent detailed mapping. The batholith core of Butte Quartz Monzonite is discontinuously flanked by plutons of granodiorite and of still more mafic rock, all denser than Butte Quartz Monzonite. These relations are brought out in Figure 8, which shows only Butte Quartz Monzonite and rocks more mafic than quartz monzonite overprinted on the relevant part of Burfeind's Bouguer gravity map (1967, Pl. 1). The main mass of Butte Quartz Monzonite is represented by a distinct gravity low. In the northern, southern, and eastern parts of the mapped area, every gravity high can be related to known plutons of granodiorite or more mafic composition; therefore, it is reasonable to assume that concealed similar relatively mafic bodies are largely responsible for the gravity high that trends along the largely covered west side. If a low-density core of quartz monzonite is separated from medium-density sedimentary rocks and underlying high-density basement rocks by a partial ring of medium-density plutons, as appears to be the case, interpretation of bottom configuration becomes most complicated. Certainly thinkable is a floor considerably deeper than the 15 km maximum proposed by Bonini but presumably above the base of the crust, which in this region is 45 to 50 km thick, according to Steinhart and Meyer (1961, p. 340, 341).

The similar trends and spacing of the gravity contours (Fig. 8) on both sides of the batholith

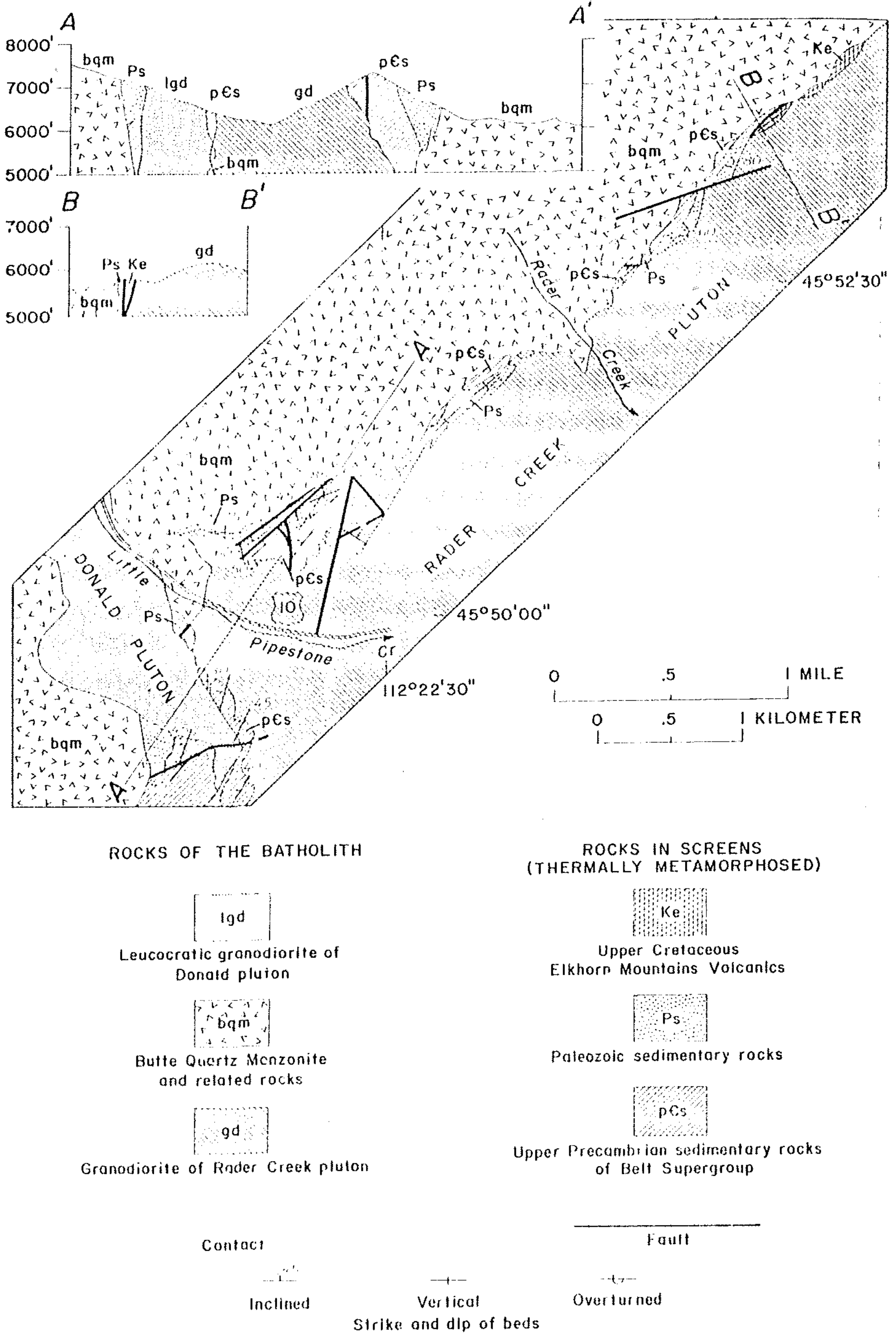


Figure 7. Near-vertical screens of intensely deformed and thermally metamorphosed country rocks between the Butte Quartz Monzonite and the Rader Creek pluton. Note similar screen between the Rader Cre pluton and the younger Donald pluton.

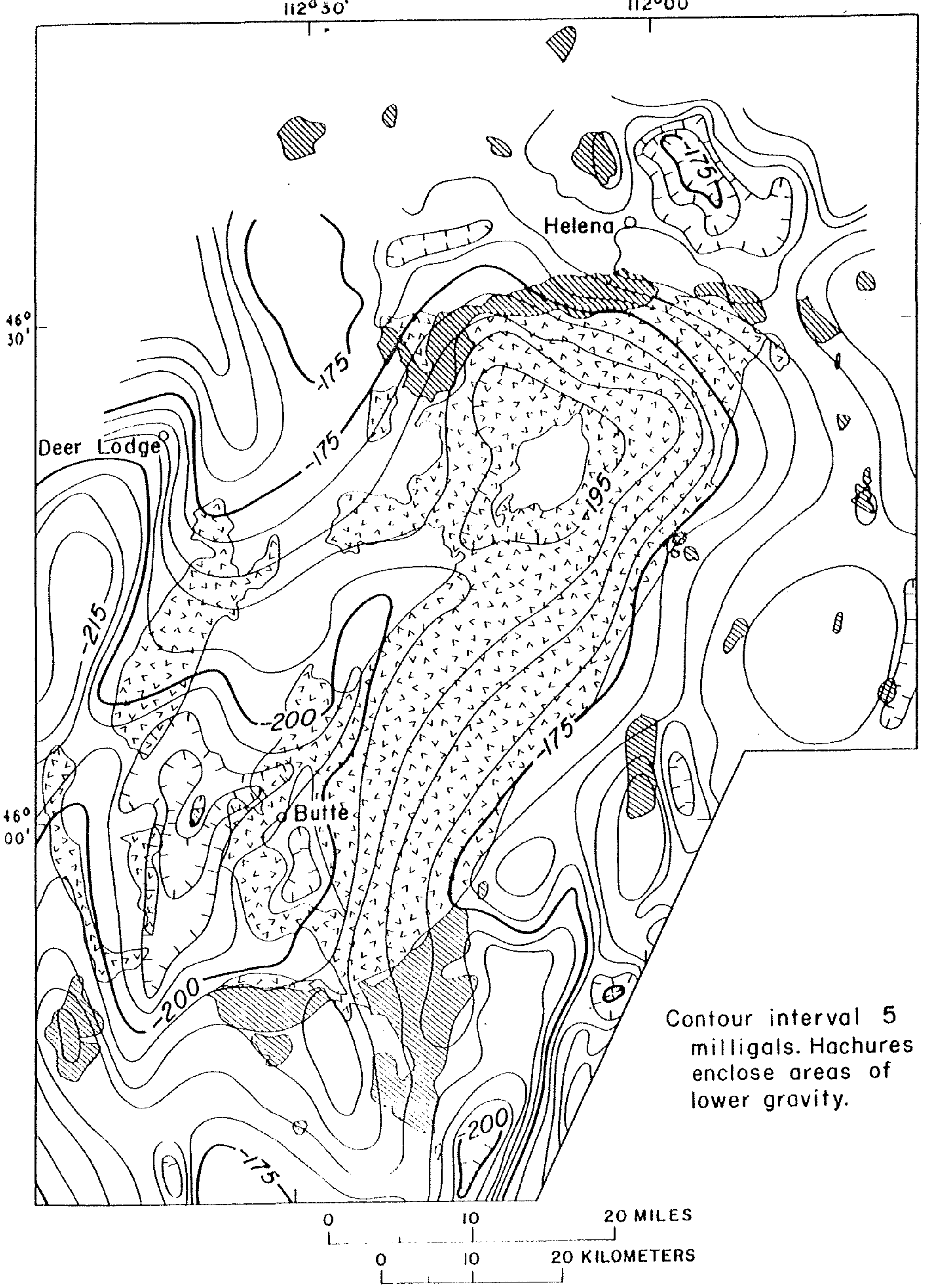


Figure 8. Bouguer gravity map of Boulder batholith, southwestern Montana, *by* Burfeind (1967). Reduced from original scale of 1:250,000. Outcrops of Butte Quartz Monzonite (Kbqm; light stipple) and of plutonic rocks (dark shading) more mafic than Kbqm added from Figure 2.

further suggest that the dip of the west flank of the batholith, beneath its cover of younger rocks, is about as steep as that of the exposed east flank. Just as the steep east flank is the result of prebatholith faulting (Smedes, 1966, p. 98), so might the west flank be. Although the east side of the Deer Lodge Valley (along the trend of the steep gradient) may be partly controlled by postbatholith faults, it is significant that there are prebatholith faults on this same trend (Smedes, 1967) which are similar and subparallel to those along the east margin. Burfeind (1967, p. 38) considers a symmetrical northwest-southeast cross section, and finds that such a solution produces "reasonable agreement between observed and computed gravity anomalies" but he nevertheless prefers the interpretation that the batholith is "a tabular mass that dips at a low angle to the northwest." Bonini (1969, p. 4 *and* Fig. 4), however, considers the batholith to be essentially symmetrical from northwest to southeast.

The model of the batholith as a thick steep-sided mass of quartz monzonite bordered by more mafic rocks is also supported by aeromagnetic data. An aeromagnetic map by Johnson and others (1965) at 1:250,000 scale, based on flights at 10,500 ft barometric elevation, spaced 2 mi apart, and having a magnetic contour interval of 20 gammas, has been redrawn to the scale of Figure 8 for comparison (Fig. 9). A partial ring of strong magnetic highs corresponds closely with exposed plutons of granodiorite and more mafic rocks; elevated tracts of Elkhorn Mountains Volcanics may contribute to highs, locally. The only other conspicuous high, 25 km southeast of Helena, probably signals subsurface masses of mafic rocks similar to those cropping out nearby. Magnetic lows characterize the Butte Quartz Monzonite and nearly all other rocks as well. Even more clearly than the gravity map, the magnetic map shows that the concealed west flank of the batholith probably has a configuration similar to that of the east flank.

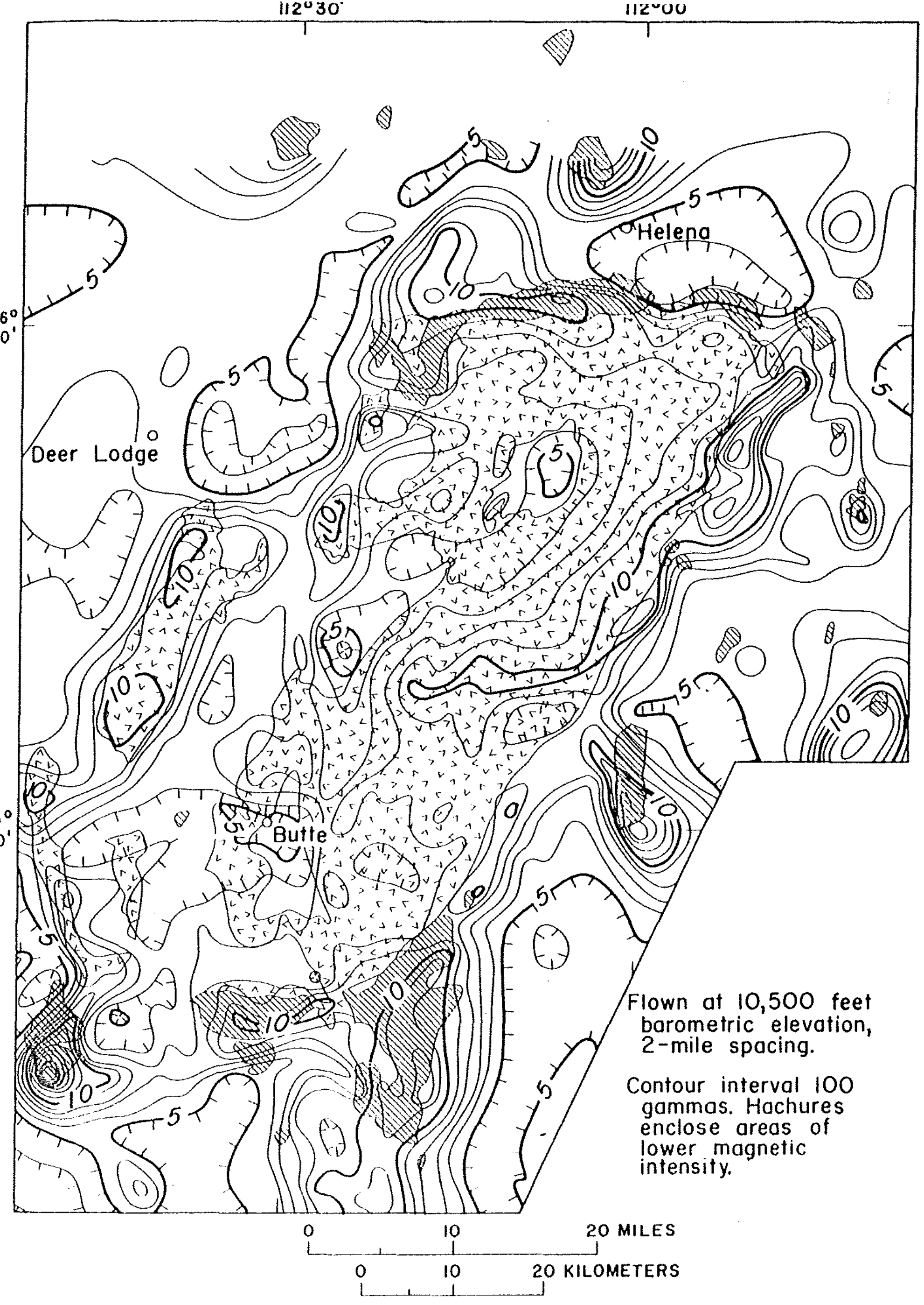
Heat flow data bear on the problem of batholith depth. Tilling and Gottfried (1969, p. E18-E19) calculate that the heat flow of $2.2\,\mu$ cal/cm^2 sec measured near Butte could be attributed entirely to radiogenic heat produced by a column 25 to 35 km thick of rock having a composition of average exposed batholith rocks (close to Butte Quartz Monzonite). This interpretation fits our thesis but, unfortunately, is not very realistic. If it were true, the 10 to 25 km of rock of the remaining crust is contributing no heat, and neither is the mantle. It may be reasonable to assume that little radiogenic heat is being contributed by any sedimentary rocks (6 to 7 km thick at the surface) or their metamorphic equivalents that may underlie the batholith, but such an assumption is unreasonable for the gneissic rocks of the basement and for the lowest part of the crust and the upper mantle.

Some heat must be furnished by sub-batholith materials, and the thickness of radioelement-rich batholith rock (largely Butte Quartz Monzonite) required to yield the observed flow of heat is, of course, reduced to that degree. Roy and others (1968, p. 6, 9) conclude that heat flow from the lower crust and upper mantle is about $1.4\,\mu$ cal/cm^2 sec in the Basin and Range heat flow province, which in their usage includes the Boulder batholith. This is two-thirds of the flow of $2.2\,\mu$ cal-cm^2 sec measured beneath Butte, consequently, a uniformly radioactive batholith column only 8 to 13 km thick would suffice.

It is, however, most unlikely that the batholith is uniformly radioactive vertically. Rather, it is probably more mafic and less radioactive with depth; if so, this would increase the thickness of batholithic rocks needed to furnish the observed heat flow.

Considerable volumes of postbatholith calc-alkalic volcanic rocks lie on or near the batholith, and some account must be taken of the possible contribution of their former magma chambers, presumably in or not far below the batholith, to present heat flow. It would appear that such sources of heat are small and tend to balance out, for the postbatholith volcanics seem to be about equally divided between rhyolite, whose heat yielding capacity is about 140 percent greater than that of Butte Quartz Monzonite, and quartz latite, whose productivity is only about 70 percent (Tilling and Gottfried, 1969, Table 6, p. E17).

One final tenuous line of evidence bearing on batholith depth is provided by the scanty refraction seismic data. Beneath Sailor Lake near the batholith, Steinhart and Meyer (196 p. 341) recognized a high-velocity (7.4 km/sec) and relatively dense layer about 23 km thick below the relatively light low-velocity (5.95 km/sec) layer cited previously, and above mantle rocks (7.94 km/sec). The relatively dense layer perhaps represents baseme rocks; the relatively light layer, batholith pl underlying Belt and Phanerozoic stratifi rocks; if the stratified rocks are compressed



igure 9. Aeromagnetic map of Boulder batholith, uthwestern Montana, reduced and generalized *from* hnson and others (1965). Total intensity magnetic ld, relative to arbitrary datum (0 3,100 gammas on original). Original publication scale 1:250,000, contour interval 20 gammas. Outcrops of Butte Quartz Monzonite (Kbqm; light stipple) and of plutonic rocks (dark shading) more mafic than Kbqm added from Figure 2.

the batholith is as much as 18 km thick.

None of the foregoing geophysical approaches offers compelling evidence. Taken altogether, however, they distinctly favor a batholith that is at least twice, and possibly four or five times, as thick as visualized by Hamilton and Myers.

Was it Emplaced by Lateral Flowage, and Quickly?

The primary features of the batholith—its over-all shape and its border relations—being inconsonant with emplacement by lateral flow, it is not surprising to find the secondary features likewise inconsonant. If the Butte Quartz Monzonite is a single thin sheet, it would have flowed in quickly enough to avoid freezing en route, and would have developed appropriate flow structures. The batholith shows abundant though mostly subtle internal flow structures, which invariably suggest steep upward motion (Grout and Balk, 1934, p. 885-888; Smedes, 1966, p. 68, 74, 98-99; 1967).

We do not contest Hamilton and Myers' statement (p. C22) that "horizontal flow [is] shown by internal structure in the west part of the batholith," but note that the reference must be to the crude layering of varieties of batholithic rocks reported by Ruppel (1963, p. 37) beneath a roof remnant east of Deer Lodge; the layers are "about parallel to stratigraphic units" in the overlying gently folded roof rocks and, as Ruppel concluded (p. 38), the magma no doubt flowed laterally here, controlled by a "structurally and stratigraphically favorable zone" beneath a roof "perhaps about 5,000 feet" thick. Local channeling of magma movement by the roof is to be expected regardless of the gross direction of travel.

More difficult is the matter of emplacement duration. Just how quickly a sheet of these dimensions ought to come to rest is hard to determine. Nevertheless, a single giant sheet, like a lava flow, must at least flow faster than it freezes, and if freezing time can be calculated, this will set an upper limit, presumably an extreme one, on the time necessary for emplacement. The time needed to consolidate sheet-like masses of magma can be approximated by the method of Jaeger (1957). Lovering (1961, p. 72) used Jaeger's method to estimate consolidation time for a body comparable in size and composition to the Boulder batholith as visualized by Hamilton and Myers; namely, a quartz monzonite sheet a few kilometers thick, intruded under a cover half as thick. By Jaeger's method, cooling a mass 5 km thick from 1000° C to 400° C requires about 400,000 yrs.

But, as the K-Ar determinations of Figure of this paper (reproduced *from* Tilling and others, 1968) show, the Butte Quartz Monzonite required at least 4 m.y. to cool enough for biotite and hornblende phenocrysts to retain argon. If the quartz monzonite mass was emplaced in a geologically brief time, it must have been far thicker than 5 km to have taken so long to cool this much. A thin body might have taken 4 m.y. to cool had it been emplaced piecemeal in appropriately spaced increments, but if so, it should exhibit internal chilled contacts between increments; careful search by many workers has failed to detect such relations within the Butte Quartz Monzonite. Cooling evidence, though hardly compelling, nevertheless raises serious doubt that the Butte Quartz Monzonite could have been emplaced as a thin sheet at shallow depth. It is worth noting that if the Butte Quartz Monzonite were as deep as it is wide—50 km—its theoretical consolidation time calculated by Jaeger's method would approach 4 m.y.

IS THE BOULDER BATHOLITH A BATHOLITH?

If the Boulder batholith did not form as a gigantic mantled lava flow, how did it form? If it is not shaped like a sheet, what is its shape? Answers to these and related questions require more detailed information and treatment, including geophysical models and a detailed geologic history, than the limited scope of this preliminary paper affords. Here, we wish merely to note that published data, and the new data offered in this paper, indicate that the Butte Quartz Monzonite, with or without its attendant mafic and silicic satellites, is a proper epizonal batholith: an extensive steep-sided pluton of granitic composition, intruded transgressively from below under a cover a few kilometers thick, and occupying a large fraction of the total thickness of the crust.

The hypothesis that the Boulder batholith is a gigantic lava flow that advanced across a broad basin, mantled only by its own ejecta, is compatible with some of the field and laboratory evidence, but incompatible with other evidence of critical importance. Accordingly examples of extrusive or quasi-extrusive thin batholiths must be sought elsewhere.

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Late Paleozoic Glaciation: Part III, Antarctica

ABSTRACT

Like other Gondwanaland fragments, Antarctica was glaciated during the late Paleozoic, as demonstrated by striated floors and boulder pavements and by glacially striated clasts in diamictites and associated varvelike strata. Tillites are known throughout the Transantarctic Mountains from the vicinity of Ross Island to the Pensacola Mountains, as well as in the Ellsworth Mountains in West Antarctica. These strata apparently were laid down in three basins (Ellsworth-Pensacola basin, Horlick-Queen Maud basin, and Beardmore basin).

Ice flowed into the Ellsworth-Pensacola basin from a major center located in the region of the eastern Weddell Sea, possibly beginning in the early Carboniferous. The Thiel salient, separating the Ellsworth-Pensacola and Horlick-Queen Maud basins, yielded some debris northward into the former basin but served primarily as a major gathering ground for ice which flowed westward into the Horlick–Queen Maud basin. Similarly, the western Queen Maud Mountains, where tillites are thin or absent, was a local center for ice flowing eastward into the Horlick–Queen Maud basin and probably westward into the Beardmore basin, although the latter direction is not yet proven by striae patterns. A major center of ice accumulation also seems to have existed in northern Victoria Land, whence flow was toward the southeast. The Ellsworth-Pensacola basin was a continuously depressed Paleozoic downwarp of major proportions, whereas the Permian Horlick–Queen Maud and Beardmore basins were shallow depressions and possibly connected.

The center of late Paleozoic glaciation may have migrated across Antarctica from the Weddell Sea region (early Carboniferous) to northern Victoria Land (Permian), judging from the meager paleontological data and stratigraphic considerations. This would be in keeping with the relative-motion curves of the paleomagnetic poles for the reconstructed Gondwanaland fragments of South America, Africa, and Antarctica, the late Paleozoic segments of which cross Antarctica from the Weddell Sea to Victoria land.

INTRODUCTION

Late Paleozoic glacial rocks were discovered in Antarctica in 1960 (Long, 1962) and are now known to occur throughout a wide stretch of the Transantarctic Mountains, as well as in the Ellsworth Mountains of West Antarctica (Craddock and others, 1964). Their recognition in Antarctica is of particular significance because of the often expressed view that Antarctica is a drifted fragment of the ancient supercontinent, Gondwanaland, and hence, should contain its own counterparts of the Paleozoic-Mesozoic Gondwana sedimentary sequence. The glacial strata of Antarctica occupy the same statigraphic positions as do glacial rocks in the Gondwana sequences of southern Africa and South America, although ages over the southern hemisphere range from at least middle Carboniferous to Permian.

Detailed studies have been carried out at many Antarctic localities, so that regional synthesis is now possible. Determination of paleogeographic trends in Antarctica (Frakes and Crowell, 1968a) is also of significance in establishing the relative position of the polar continent in the Gondwanaland framework. Because major breakup of Gondwanaland did not occur until after glaciation took place, the distribution of continental ice, and especially the directions of flow as recorded in the glacial deposits, can be used as an aid in matching Antarctica with the other Gondwanaland fragments. For Antarctica, however, conclusions are less certain than for the other continents, because so much of the continent is covered with ice, and so much of it has not yet been fully explored.

In the Transantarctic Mountains, late Paleo-

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