

Cenozoic Block Uplifts in East-Central Idaho and Southwest Montana

By EDWARD T. RUPPEL

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*An interpretation of the linear mountain ranges of
east-central Idaho as drape-folded, basement-
cored block uplifts similar to the block
uplifts of southwest Montana*



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CENOZOIC BLOCK UPLIFTS IN EAST-CENTRAL IDAHO AND SOUTHWEST MONTANA

By EDWARD T. RUPPEL

ABSTRACT

The northwest-trending linear mountain ranges of east-central Idaho commonly have been considered to be basin-ranges bounded on one or both sides by large normal faults. Geologic studies in the Lemhi Range and Beaverhead Mountains suggest, however, that these ranges are structurally flat-topped block uplifts, flanked by monoclinical folds. The monoclinical folds are interpreted as drape folds, in which sedimentary rocks, earlier deformed by regional thrust faults, have been passively folded over the edges of deeper, rising blocks of crystalline basement rocks, although no basement rocks are exposed in these ranges. The normal faults that outline the present mountain ranges are thought to be relatively minor, secondary faults formed by gravitational collapse and sliding of sheets of rock from the steepened monoclinical limbs of the uplifts into the adjacent valleys. The normal faults suggest extensive gravitational denudation of sedimentary rocks from the block uplifts, and the denudational sheets probably form a significant part of the fill in adjacent valleys.

The basement-cored block uplifts of southwest Montana are known to be bounded by steep reverse faults that are partly of Precambrian ancestry. The thin veneer of sedimentary rocks above these blocks was drape folded, and the ranges largely have been denuded by gravitational sliding. The trends of the ranges in southwest Montana are partly similar to those in Idaho, and the Idaho ranges are inferred also to be controlled by steep reverse faults, which first formed in the Precambrian, and which bound the concealed blocks of basement rocks.

The mountain ranges of both east-central Idaho and southwest Montana thus are inferred to be drape-folded, basement-cored, and basement-controlled block uplifts. The main difference is in the thick veneer of sedimentary rocks above the basement cores in Idaho, and the relatively thin veneer in Montana.

The major uplift of the mountain blocks took place in Miocene time and was essentially vertical because the uplifts are structurally nearly flat on top. Most gravitational sliding and denuding of the ranges was contemporaneous with uplift, on linear zones of secondary normal faults that parallel the monoclinical limbs of the uplifts. Young normal faults made conspicuous by Pleistocene and Holocene fault scarps are not a product of the major, regional block uplifting, but rather appear to be minor extensional faults related to late Tertiary and Quaternary regional arching north of the Snake River Plain.

The northwest- and east-trending steep reverse faults that define and bound the basement blocks apparently also controlled the emplacement of intrusive igneous rocks and related mineral deposits. The principal stocks and all the known major deposits of metallic minerals in east-central Idaho are on the monoclinical limbs of the block uplifts, above the reverse faults inferred at greater depth. The distribution suggests that magma rose in reverse fault zones to the base of the Medicine Lodge thrust system, and there the magma spread laterally

in sheets in imbricate thrust faults. The principal mineral deposits are around necklike stocks, which fed the sheets, and only small mineral deposits, few of which have yielded any ore, are known around the sheets. Substantial ore bodies have not been found in the structurally flat, central parts of the block uplifts; and ore bodies are not likely to have been deposited in the central parts of the block uplifts because the seemingly necessary deep structural controls are not present there.

INTRODUCTION

The Lemhi and Lost River Ranges in east-central Idaho and the Beaverhead Mountains along the Idaho-Montana State line are long, northwest-trending ranges separated by equally long, linear intermontane valleys. In contrast, the ranges in southwest Montana mostly are short mountain masses with diverse trends, nearly surrounded by broad, interconnected basins (fig. 1). The different topographic patterns of the mountain ranges are accompanied by changes in structural pattern from central Idaho eastward into southwest Montana, across the leading edge of the Cordilleran fold and thrust belt (fig. 2), that seem to indicate that this is a region where two significantly different structural provinces come together and overlap. West of the leading edge of the thrust belt the structure is highly complex and includes major thrust faults, tight asymmetric folds, steep reverse faults, and widespread normal faults, but to the east the structural pattern is that of basement-cored block uplifts and simple draped folds. These differences prompted earlier division of the region into a western fold-thrust, or Sevier province, and an eastern foreland or Laramide province.

The division into structural provinces exaggerates the differences across the region and obscures relations that suggest that the western province and the eastern province are structurally similar. The linear, fault-bounded ranges of east-central Idaho appear to be drape-folded uplifts above basement blocks of crystalline metamorphic rocks—similar to the basement-cored block uplifts of southwest Montana, and most of the post-thrusting steep normal and reverse faults of the

CENOZOIC BLOCK UPLIFTS, IDAHO, MONTANA

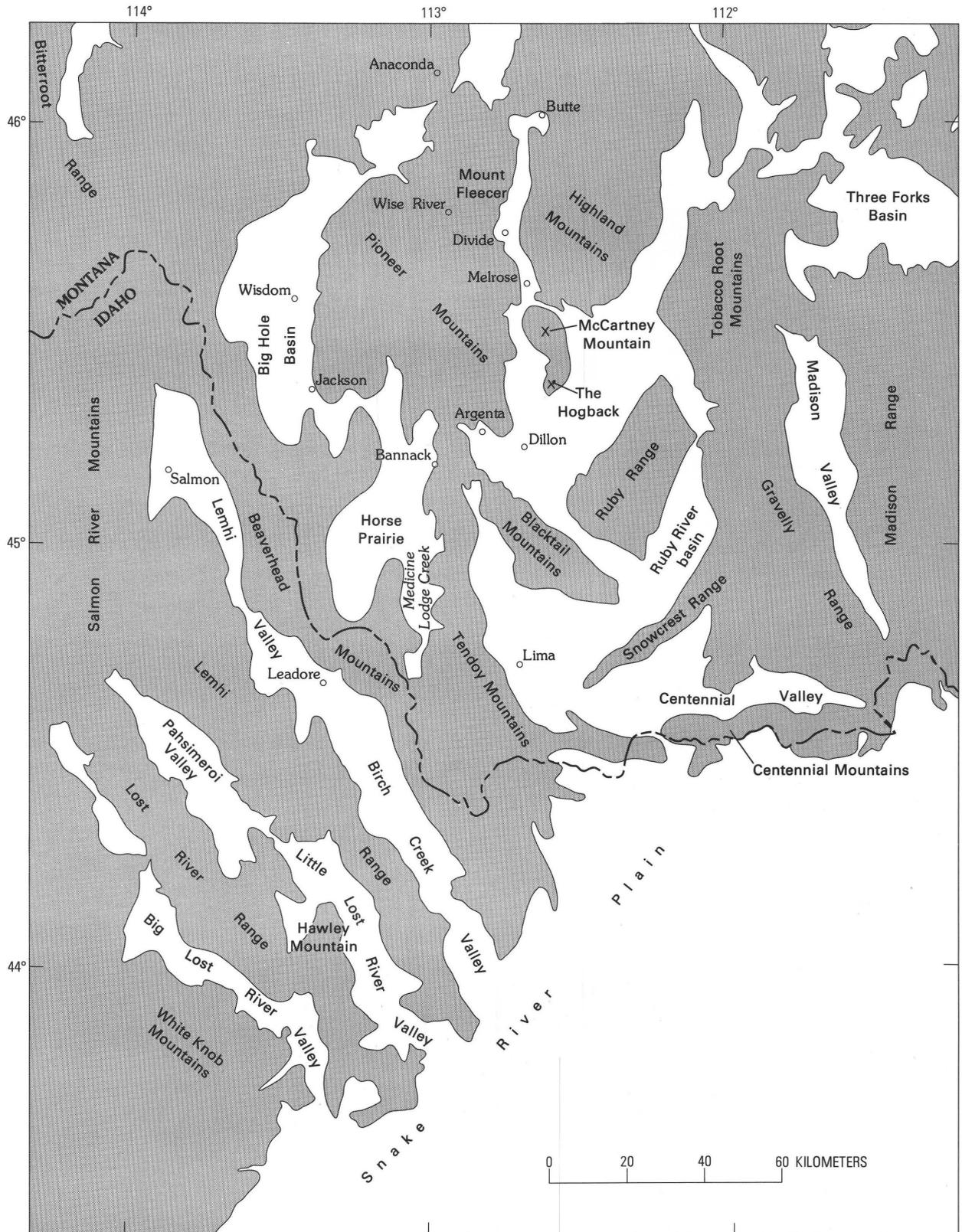


FIGURE 1.—Index map of east-central Idaho and southwest Montana. Mountain areas are stippled.

region are a result of mainly vertical differential movements on discrete basement blocks, that were, however, first defined in Precambrian time. The two structural provinces are really only one, of basement-cored block uplifts, and the apparent differences in the two regions are due mainly to a much thicker sequence of thrust-faulted sedimentary rocks, above crystalline basement rocks, in the western province.

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SUMMARY OF EARLIER STUDIES

The great, flat thrust faults that dominate east-central Idaho and much of southwest Montana also dominate much of the literature on the region; the steep normal and reverse faults that are present throughout the region (fig. 2) generally have not been discussed in much detail. The steep faults bounding the linear ranges of east-central Idaho were first noted by Meinzer (1924, p. 15) and were discussed in a little more detail a few years later by Kirkham (1927, p. 27-29), who considered them to be steep thrust faults, bounding wedge uplifts. Shenon (1928, p. 5) briefly described faulting in the Birch Creek Valley and considered this valley to be a graben, bounded by steep, normal faults, a view subsequently extended to the other valleys of east-central Idaho by A. L. Anderson (1934, p. 19-21). Anderson (1934, p. 26-28) also discussed the age of normal faulting and concluded that most faulting had taken place in Pliocene and Pleistocene time. Ross (1947, p. 1139) and Baldwin (1951), who described normal faults in the Lost River and Lemhi Ranges, agreed that much faulting was relatively recent, but they suggested that some normal fault movement occurred earlier, perhaps in Oligocene and Miocene time. Baldwin (1951, p. 885, 899) also concluded that the ranges of east-central Idaho had been tilted downward to the northeast, so that the intervening valleys are not fault-bounded structural trenches, but rather are sediment-filled troughs on the back slopes of the tilted fault blocks, a conclusion also reached by R. A. Anderson (1948, p. 11) and by Skipp and Hait (1977, p. 499-509) for the Lemhi Range.

The block uplifts of southwest Montana were discussed first by Klepper (1950, p. 73-76), who described them as domal uplifts first outlined in Late Cretaceous

time and modified by later Cenozoic doming and Pliocene and Pleistocene normal faulting. Pardee (1950, p. 375-377, 385-386) described the mountain ranges of southwest Montana mostly as tilted fault blocks formed as a result of normal faulting in Pliocene and early Pleistocene time.

Scholten, Keenmon, and Kupsch (1955, p. 383-389) recognized both normal faults and steep reverse faults in the Lima, Mont., region, and, like their predecessors, they recognized that at least the normal faults had been active in recent time. Scholten (1957; 1968, p. 109-113), following Sloss and Moritz (1951, p. 2138), divided southwest Montana into shelf and geosynclinal provinces separated by a tectonic hinge zone about in the southern part of the Beaverhead Mountains, and so first clearly suggested the separation into an eastern province of basement-cored uplifts and a western province of complex folding, thrusting, and basin-range faulting.

The Ruby Range block uplift was mapped and described by Tysdal (1970, 1976a, b), who concluded that uplift of the range and folding of the sedimentary rocks was a result of differential vertical movements of discrete basement blocks (Tysdal, 1970, p. 105-119). Swanson (1970, p. 670, 718-719) interpreted most of the steep faults of southwest Montana as reverse faults reflecting vertical movements along ancient shear zones, and he attributed much of the folding in this region to draping over uplifted, fault-bounded, rigid basement blocks of Archean crystalline rocks.

Most recently, the separation into structural provinces first discussed by Scholten (1967) was reaffirmed by Beutner (1977, p. 353-354), who applied the names Sevier belt to the fold-thrust province on the west, and Laramide belt to the region of basement-cored uplifts on the east; he stated that "****the terms Laramide and Sevier thus become useful in describing the parallel belts of contrasting structural character ***."

REGIONAL STRUCTURAL TRENDS

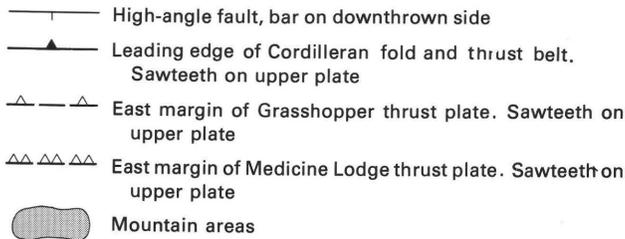
The steep faults of southeast Montana and east-central Idaho include reverse, normal, and strike-slip faults that have similar trends throughout the region; the dominant trends are near northwest, east, northeast, and north (fig. 2). Most of the steep faults seem to reflect repeated movement at different times from the Precambrian to the near present, and some suggest different kinds of movement at different times. The major trends, however, appear to have been established in the Archean crystalline rocks before deposition of any of the younger sedimentary rocks (Vitaliano and Cordua, 1979, p. 6). In southwest Montana, the steep faults reflect



FIGURE 2 (above and facing page).—Sketch map of major steep faults in east-central Idaho and southwest Montana.

EXPLANATION

1. Willow Creek fault zone
2. Camp Creek fault
3. Spanish Peaks fault zone
4. Gravelly Range thrust zone
5. Snowcrest-Greenhorn thrust
6. Centennial fault
7. Red Rock fault
8. Horse Prairie fault
9. Miner Lake-Beaverhead Divide fault zone



recurrent movement of Precambrian northwest- and east-trending faults, or later development of faults about parallel to Precambrian northeast-trending foliation or faults and north-trending folds and shear zones.

The structural trends throughout the region are essentially the same as those of central and northwest Wyoming, the type "Wyoming Province" of block uplifts, and partly they are a direct extension of the Beartooth and Grayling Creek block uplifts into southwest Montana (Foose and others, 1961, p. 1162-1163; Prucha and others, 1965; Becraft and others, 1966, p. B8-B10; Ruppel, 1972, p. A49-A50).

NORTHWEST-TRENDING FAULTS

The clearest evidence for the antiquity of structural trends is in the northwest- and east-trending faults that cut Precambrian crystalline rocks in southwest Montana. Northwest-trending faults in the Ruby Range contain diabase dikes of Precambrian age; the earliest movement on the faults was left-lateral strike slip, which was followed by intrusion of the diabase dikes, and by later reverse and normal fault movements in Late Cretaceous and Cenozoic time (Mann, 1954, p. 50; Heinrich, 1960, p. 16-17; Tysdal, 1970, p. 103-111; Garihan, 1973, p. 164-165; 1976, p. 19; Vitaliano and Cordua, 1979; Schmidt and Garihan, 1979, p. 301). Late Precambrian diabase dikes in the Ruby Range and in the southern part of the adjacent Tobacco Root Mountains have yielded Rb-Sr intrusive ages of about 1,450 m.y.

(million years) and 1,120 m.y. (Wooden and others, 1978, p. 474). Diabase dikes are not known to intrude most of the other northwest-trending faults of the region, but the structural trend, reflected in both reverse and normal faults is pronounced, and these faults have been the sites of some of the most ancient and most recent movements. These faults include the great Spanish Peaks reverse fault zone in the Madison Range (Iddings, 1904, p. 99; Becraft and others, 1966, p. 89), and widely distributed subparallel faults that break the crystalline rocks and younger sedimentary rocks in the Tobacco Root Mountains (Reid, 1957, p. 17-18; Levandowski, 1956, p. 184-192; Vitaliano and Cordua, 1979), Ruby Range (Heinrich, 1960, p. 17; Tysdal, 1970, p. 105-111; Garihan, 1976), Blacktail Mountains (Klepper, 1950, p. 73-74), and Highland Mountains (M. R. Klepper, written commun., 1976; Smedes, 1968). Northwest-trending reverse and normal faults are common in the Tendoy Mountains and in the valley of Medicine Lodge Creek (Scholten and others, 1955, p. 383-389), and, in east-central Idaho, normal faults, partly accompanied by young fault scarps, flank northwest-trending structural trenches. Farther north, on the crest and west side of the Beaverhead Mountains near Salmon, Idaho, the northwest-trending Miner Lake-Beaverhead Divide fault zone is the westernmost major reverse fault zone known to be exposed in this region (MacKenzie, 1949; Tucker, 1975, p. 136-146; Ruppel, 1978, p. 8), and the principal fault zone in east-central Idaho known to have first formed in Precambrian time. Other reverse faults with similar trends but small displacements have been described in and near Salmon River Mountains farther west (A. L. Anderson, 1956, 1959).

EAST-TRENDING FAULTS

The best known east-trending fault zone is the Willow Creek zone (fig. 2), which was named and described by Robinson (1963, p. 103) as a fault that formed in pre- and intra-Lahood Formation (Proterozoic Y) time at the north end of the Tobacco Root Mountains. McMannis (1963, p. 416-417), Robinson (1963, p. 107), and Schmidt, Brumbaugh, and Hendrix, (1977, p. 760) described other faults along both east and west extensions of the Willow Creek zone. McMannis and Robinson also discussed the evidence for movement on extensions of the Willow Creek zone before and during deposition of the Belt Supergroup in Proterozoic Y time, for continued movement after deposition of the Belt Supergroup but before deposition of the Middle Cambrian Flathead Sandstone, and for lateral movement in Late Cretaceous and early Tertiary time (see also Harrison, 1972, p. 1216-1218; Harrison, Griggs, and Wells, 1974). Mc-

Mannis (1963, p. 423-424) described the east-trending Camp Creek fault, in the southwest part of the Highland Mountains, and he suggested that it has had a history of Precambrian and later movement similar to that on the Willow Creek zone. The Horse Prairie fault zone (Ruppel and Lopez, in press), farther south (fig. 2), formed the south end of the Belt seaway and is similar to both the Willow Creek and Camp Creek faults. The latest movements on the Horse Prairie fault zone disrupted the courses of present streams, and reintegration of drainage across the fault is not complete. All these major east-west faults controlled southern depositional limits of Belt Supergroup or equivalent rocks in part or all of Proterozoic Y time, and they were reactivated as strike-slip faults in Late Cretaceous and early Tertiary time. At least the Horse Prairie fault zone seems to have moved recurrently through Cenozoic time to the present.

Two east-trending faults north of Bannack, Mont., (fig. 2) are only partly mapped and are not well known. The southernmost of these has been mapped in Badger Pass, northwest of Bannack (Lowell, 1965), and continues from there westward across the south end of the Pioneer Mountains to form the north margin of the basin terminated on the south by the Horse Prairie fault. The fault appears to cut Tertiary rocks and younger deposits east of Badger Pass, but it has not been mapped in that area; it may extend at least as far east as Dillon, Mont. The northern fault is marked by fault scarps on the Big Hole Divide, about 15 km east of Jackson, Mont., and seemingly extends west from there to control the upper end of the Big Hole basin. Both of these faults cut Tertiary and Quaternary rocks and deposits, as well as older rocks, and partly bound major basins filled with Tertiary rocks. They seem likely to be old faults that have moved recurrently, like other east-trending faults in southwest Montana.

The Centennial fault, flanking the north side of the Centennial Mountains, is the only other major, east-trending fault known in southwest Montana (fig. 2). The fault is near the southern margin of cratonic Precambrian crystalline rocks in southwest Montana, and in this respect, as well as in its trend, it resembles other east-trending faults of the region. Unlike the other east-trending faults, however, the Centennial fault has been interpreted to be a normal fault, downthrown on the north in Cenozoic time (Pardee, 1950, p. 374-376; Witkind, 1977, p. 534); an explanation for its divergent trend in a region thought to be characterized by northwest- and northeast-trending normal faults has remained elusive. Perhaps that explanation is to be found by grouping the Centennial fault with the other east-trending faults of the region and by interpreting it to be an ancient east-trending fault zone, which controlled the southern margin of the craton in southwest

Montana and which has had a history of recurrent movement from Precambrian time through the Cenozoic like the histories of recurrent movement on the Willow Creek fault zone, the Camp Creek fault, and the Horse Prairie fault zone.

NORTHEAST-TRENDING FAULTS

Northeast-trending faults are not so clearly of Precambrian origin as the northwest- and east-trending faults. The northeast-trending faults described in and near the Ruby Range (fig. 2) are considered to be normal faults that moved recurrently in Tertiary and Quaternary time (Dorr and Wheeler, 1964, p. 328-335; Tysdal, 1970, p. 119-123; Garihan, 1976, p. 24-25). The northeast-trending Snowcrest fault, southeast of the Ruby Range, was mapped as a moderately steep, northwest-dipping thrust of early Tertiary age by Klepper (1950, p. 74-75). Hadley (1969) and Mann (1954, p. 52-53) mapped the Greenhorn thrust, north of the Snowcrest fault, as a northwest-dipping thrust, and part of its map trace suggests that it is steeper than shown in cross section. Mann (1954, p. 55-58) also described the Gravelly Range thrust zone, which includes several northeast- to north-trending reverse faults that dip 70°-75° west, and he considered both the Greenhorn and Gravelly Range faults to be Laramide in age. In the Tobacco Root Mountains, Vitaliano and Cordua (1979) mapped and described northeast-trending faults that they concluded are of probable Precambrian age but which also have moved recurrently in post-Precambrian time. Swanson (1970, p. 670, 718-719) interpreted all the northeast-trending faults of this region as high-angle reverse faults reflecting vertical movements along ancient shear zones.

The available evidence from mapping in the Snowcrest and Gravelly Ranges suggests that the northeast-trending faults there are probably steep reverse faults that locally flatten in their upper parts. (See Mann, 1954, p. 58; Prucha and others, 1965, p. 969-973.) The parallel faults that flank the Ruby Range seem most likely also to be steep reverse faults, exposed at a deeper structural level, along which there might have been some later normal fault movement, especially along the west flank of the range. The northeast-trending faults in the Ruby Range both cut and are cut by the northwest-trending faults, a relation that suggests only that Late Cretaceous and younger movements on northeast and northwest faults have been nearly contemporaneous.

The Precambrian origin of northeast-trending faults and shear zones, inferred by Swanson (1970) and suggested by Vitaliano and Cordua (1979), is not clearly demonstrated by the geologic maps and descriptions of the region. A prominent northeast trend, parallel to the faults, is evident in the foliation and bedding of the

crystalline metamorphic rocks in both the Ruby Range and Tobacco Root Mountains (Levandowski, 1956, p. 177-180; Heinrich, 1960, p. 16; Reid, 1963, p. 297; Burger, 1969, p. 1334-1340), but no northeast-trending faults demonstrably of Precambrian age are known. The available evidence shows that the faults moved in Late Cretaceous time, along lines subparallel to Precambrian foliation and further segmented blocks already defined and bordered by older northwest- and east-trending faults. But the evidence does not show conclusively that the faults are controlled by the foliation or by older faults. (See Prucha and others, 1965, p. 989-992.)

NORTH-TRENDING FAULTS

The north-south structural trend is not as conspicuously developed as the other trends, although north-trending strike-slip faults are common in the western part of the region, and a few north-trending faults cut crystalline rocks farther east along the west side of the Tobacco Root Mountains and on the east side of the Ruby River basin (fig. 2) (Reid, 1957, p. 19; Dorr and Wheeler, 1964, p. 330). All these faults appear to be of Tertiary and Quaternary age.

Reid (1957, p. 19; 1963, p. 299-301) described north-trending open folds, of post-metamorphic Precambrian age, and north-trending shear zones of Tertiary age in the northern part of the Tobacco Root Mountains; and Burger (1969, p. 1329) described north-trending open folds and joints thought to be of Precambrian age in the southern part of the Tobacco Roots.

In summary, most of the steep faults in southwest Montana and east-central Idaho are parallel to Precambrian structural trends developed during or shortly after metamorphism in the older Precambrian crystalline basement rocks of this region, but only northwest- and east-trending faults clearly reflect recurrent movement along Precambrian faults. Basement control of structural features is evident in the basement-cored, fault-bounded, segmented block uplifts of southwest Montana. The mountain ranges farther west are linear rather than segmented. The structural trends are the same as in the eastern ranges, but basement rocks are not exposed, and basement controls can only be inferred.

DIFFERENCES IN THE VENEER OF SEDIMENTARY ROCKS

The sedimentary rocks east of the leading edge of the Cordilleran fold and thrust belt in southwest Montana (fig. 2) are very different from those to the west in sequence, age, lithology, and thickness; these differences prompted the division of the southwest Montana and

east-central Idaho region into shelf and geosynclinal stratigraphic and tectonic provinces. More recent studies have shown that different stratigraphic sequences are present on the craton—east of the thrust belt, and in different parts of the thrust belt (Ruppel, 1978; Skipp and Hait, 1977; Ruppel and Lopez, in press)—and that the rocks formerly included in the geosynclinal province are indeed geosynclinal, but have been transported far east of their depositional region by movement in major thrust plates. The rocks of the region have been described in many reports, and only a little needs to be said about them here, to emphasize the differences between the eastern and western sequences and to stress the intense imbricate thrust faulting in the western sequence—because the great thickness and complex imbrication of the western rocks were significant factors influencing the expression of mid-Cenozoic tectonism.

The sedimentary rocks of the cratonic sequence are at most about 3,300 m thick. The basal sedimentary rocks are of Cambrian age, overlying Precambrian crystalline basement rocks. Paleozoic rocks above the basal Cambrian sandstone are mainly limestone and dolomite interrupted only by a few thin shale formations and interbedded sandstones, in all about 1,600 m thick, and these are overlain by sandstone and shale that is mostly of Cretaceous age. The cratonic sedimentary rocks are drape folded and are cut by steep faults, but the structure is relatively simple.

Sedimentary rocks in the linear mountain ranges in east-central Idaho are in two layers, separated by the Medicine Lodge decollement (fig. 2): a lower layer, relatively undeformed, of micaceous quartzite and siltstone of the Proterozoic Y Yellowjacket Formation, probably more than 6,500 m thick; and an upper layer, complexly folded and thrust faulted, of younger but still Precambrian quartzitic rocks and Paleozoic quartzite, dolomite and limestone, in all more than 15,000 m thick. The rocks of the upper layer are relatively massive, but the thick units are laced with anastomosing imbricate thrust faults, and about half of the rocks are in thrust-broken, overturned limbs of nearly isoclinal asymmetric folds; these rocks after thrusting, but before high-angle faulting, probably are described best as an immensely thick sequence of imbricate thrust slices that mostly are made up of strongly fractured to shattered quartzite, limestone, and dolomite. The Medicine Lodge decollement, between the layers, is as much as 300 m thick. Crystalline basement rocks are not exposed in these ranges, except possibly in imbricate thrust slices in the Beaverhead Mountains (Ruppel, 1978, p. 18), and in two large boulders of schist, each several meters in diameter, that were inclusions in the Big Timber stock in the central part of the Lemhi Range (see fig. 10) (Ruppel and Lopez, 1981.)

Sedimentary rocks in the Grasshopper thrust plate and in the zone of imbricate thrust faults at the east edge of the thrust belt resemble those of the craton in some respects; but they differ in thickness and partly in composition, and the rocks of the Grasshopper thrust plate include Proterozoic Y sandstone and quartzite of the Belt Supergroup at least 6,000 m thick. (See Ruppel, 1978; Ruppel and Lopez, in press.)

FOLDS AND STEEP FAULTS IN THE LEMHI RANGE AND BEAVERHEAD MOUNTAINS

The fault-bounded, northwest-trending linear mountain ranges of east-central Idaho include the Lost River and Lemhi Ranges and the Beaverhead Mountains (fig. 3) and have long been interpreted as basin ranges (Meinzer, 1924). The ranges are separated by broad, open valleys, which are structural trenches that carry divided northwest and southeast drainages as a result of arching in late Cenozoic time (Ruppel, 1967). Gravity studies in the Lemhi-Birch Creek trench show that it is extremely deep—about 3,000 m in its deepest part and the deepest structural trench in eastern Idaho (Kinoshita and others, 1969). The Lemhi Range rises an additional 1,000 m or more above the present valley floor, and the Beaverhead Mountains are only a little lower, so the present structural relief from mountain crest to valley bottom, beneath the fill Tertiary rocks, is about 4,000 m (Kinoshita and others, 1969; Ruppel, 1964, p. C16). The Pahsimeroi-Little Lost River trench appears, on the basis of gravity data, to be only about half as deep as the Lemhi-Birch Creek trench (Kinoshita and others, 1969), and the total structural relief is about 2,500–3,000 m.

FOLDS IN THE LEMHI RANGE

The central part of the Lemhi Range has been described as an anticlinal fold having a complexly folded and thrust-faulted, steeply dipping eastern limb (Umpleby, 1913, p. 49; Hait, 1965, p. 164–181), but more complete mapping indicates that this part of the range is a broad, northwest-trending, nearly flat-topped uplift flanked by monoclinical limbs that dip steeply into the adjacent basins (Ruppel, 1968, 1980; Ruppel and Lopez, 1981). The rocks of the range are complexly folded, but this folding is related to thrust-faulting, which predates uplift of the range, and the thrusts themselves are not folded in the axial part of the range. The multiple imbricate thrusts in the range dip 5°–15° southwest almost everywhere in the range except on its flanks and dip into the Medicine Lodge decollement, which is

nearly flat (Ruppel, 1978; Ruppel and Lopez, 1981; Ruppel and Lopez, in press). Also, a mountaintop remnant of Tertiary boulder conglomerate at the head of Sawmill Canyon, deposited in what is now the core of the range on deeply eroded, thrust-faulted rocks, remains essentially horizontal, neither folded nor tilted (Ruppel and Lopez, 1981). The evidence of the nearly flat thrust surfaces and the horizontal boulder conglomerate indicates that the axial part of the Lemhi Range is structurally flat, and suggests that uplift of the range was essentially vertical.

The monoclinical folding on the flanks of the range commonly is both abrupt and steep. On the west flank of the range, the structure in most places is similar to that near Patterson (Ruppel, 1980) (fig. 4, sec. A–A') where imbricate thrust slices and thrust faults abruptly steepen westward at the crest of the valley wall and dip west almost as steeply as the normal faults along the west flank of the range. On the east flank of the Lemhi Range, the dips of imbricate slices and thrust faults, of rocks in the imbricate slices, and of the Medicine Lodge decollement change abruptly to the east about at the crest of the valley wall, and in places the dips are nearly vertical (fig. 4, secs. B–B' to F–F'). At Gunsight Peak (fig. 4, sec. B–B'), imbricate thrust faults that are flat or gently west-dipping farther west are abruptly folded and dip 20°–30° east (Ruppel, 1980). From Gilmore to the south end of the range almost all the thrust faults, thrust slices, and the rocks in them on the east flank of the range dip eastward, in places as steeply as 80° (fig. 4, secs. C–C' to E–E') (Ruppel and Lopez, 1981; Hait, 1965; Beutner, 1968; Ross, 1961).

FAULTS ON THE FLANKS OF THE LEMHI RANGE

The faults that cut the flanks of the central part of the Lemhi Range are steep normal and reverse faults. At Patterson Creek (fig. 4, sec. A–A'), and most other places, the west flank of the range is bounded by steeply west-dipping normal faults that cut even the youngest surficial deposits and are marked by conspicuous fault scarps. The folded thrust faults are nearly as steep as the range-front faults and could have provided slip surfaces appropriate for normal fault movement similar to that described by Beutner (1972), who discussed gravitational sliding of older thrust slices from the southern part of the Lemhi Range, westward into the Little Lost River Valley, on thrust surfaces folded by uplift of the range. On the east flank of the range, at Gunsight Peak, steep north-northwest-trending, east-dipping normal faults bound the range front (fig. 4, sec. B–B'). From Gilmore to south of Spring Mountain Canyon (fig. 4,

secs. *C-C'* to *E-E'*) the complex east-dipping monoclinical fold is broken by steep, east-dipping, north-northwest- to northwest-trending normal and reverse faults and by vertical, north-trending strike-slip faults (Ruppel and Lopez, 1981). The largest normal fault near Gilmore is 4–5 km east of the mountain front and is separated from the mountain front by a pediment (Ruppel and others, 1970, p. 17). Range-front normal faults, broken by north-trending vertical faults that probably are mostly strike-slip, bound the range everywhere to the northwest (fig. 3), but none have been mapped farther south, even though the precipitous east front of the range suggests that it probably is fault-controlled (Ross, 1961; Hait, 1965; Beutner, 1968).

RING FRACTURING IN THE CENTRAL LEMHI RANGE

A number of curving faults in the north-central part of the Lemhi Range, north of Patterson, Idaho (Ruppel, 1980), seem to differ from the more linear faults that flank the Lemhi Range. The curving faults are only partly interconnected, but taken together they outline a semicircular or semioval area about 10 km in greatest radius, centered on the west side of the range (fig. 5). The displacement on the faults where it can be determined, most commonly is down on the inside of the semicircular area. The faults are concealed in places by Quaternary surficial deposits and appear to be older than other steep faults in the range, but younger than the thrust faults, which they cut.

The semicircular area of curving faults includes nested within it two other semicircles that are strikingly outlined by deep, curving glaciated canyons. The outermost of the topographic rings coincides or merges with the fault-controlled semicircle on the south, near Patterson, and also on its northern edge in Morse Creek valley, and elsewhere it is at least partly fault-controlled. The innermost topographic ring is not so obviously fault-controlled but instead probably reflects erosion controlled by fracturing. The nested rings thus defined by curving faults, inferred fracturing, and topography, are also sites of igneous intrusions (fig. 5). All the small Tertiary granitic stocks of the area are in the outer rings, including the concealed stock at the Ima mine near Patterson with its associated deposits of tungsten, molybdenum, copper, and silver minerals. The innermost ring is intruded by andesitic and basaltic dikes related to the Challis Volcanics, as are the outer rings in a few places. The association of Challis dikes and the curving structures suggests that this complex of nested rings is related to Challis volcanism—the remnant of a Challis caldera from which the extrusive volcanic rocks

have been completely removed, so that only the curving faults, reflecting collapse above a magma chamber, remain. Only the eastern half of the caldera is exposed. If the missing western half is restored, the caldera center is about on the southwest flank of the Lemhi Range, 8–10 km north of Patterson. The oval shape of the caldera seems likely to be the result of later deformation during mid-Tertiary block uplift. (See p. 11.)

The Withington Creek caldera (D. A. Lopez, oral commun., 1979) occupies a similar position on the northeast flank of the Lemhi Range, about 15 km south of Salmon, Idaho. This small caldera, about 10 km in maximum diameter, is marked by massive Challis ash-flow tuffs at least 600 m thick within the caldera, in contact across curving faults with only 50–100 m of thinly layered ash-flow tuff and andesitic flows outside the caldera. The eastern part of the caldera is cut by northwest-trending faults along the range front.

FOLDS AND FAULTS IN THE BEAVERHEAD MOUNTAINS

The structure of the Beaverhead Mountains is similar to that of the Lemhi Range in most respects, and the Beaverheads, like the Lemhi Range, appear to be a flat-topped uplift flanked by monoclinaly folded limbs that are cut by steep faults (fig. 3). The southern part of the range has been described by Scholten and Ramspott (1968, p. 27–40) and Lucchitta (1966, p. 92–131) as an elongate domal uplift, flanked by steep reverse faults on the east and by younger normal faults on both sides. The axial part of the range is underlain by nearly flat, pre-uplift thrust faults that steepen on the range flanks, in places to as much as 80°. The central part of the range, lying east of the communities of Leadore and Tendoy, Idaho, is much the same as the southern part, but the central part is broken by north-trending strike-slip faults (Ruppel, 1964, 1968). On the top of Grizzly Hill, north of Leadore, imbricate thrust slices dip gently south and southwest at angles of 10° or less; at the crest of the Lemhi valley wall, they steepen to 35°, the same dip as that of the normal fault system in the east-trending segment of the mountain front north of Leadore (Ruppel, 1968; Staatz, 1973). The eastern edge of the central Beaverhead Mountains seems to be bounded by a northwest-trending, steeply east-dipping fault zone, but it has not been mapped.

In the northern part of the Beaverhead Mountains, the Medicine Lodge thrust plate is widely preserved and shows the same structural relations in the mountain block as farther south—and as in the Lemhi Range. The Medicine Lodge decollement and overlying imbricate thrust slices are nearly flat for many tens of kilometers

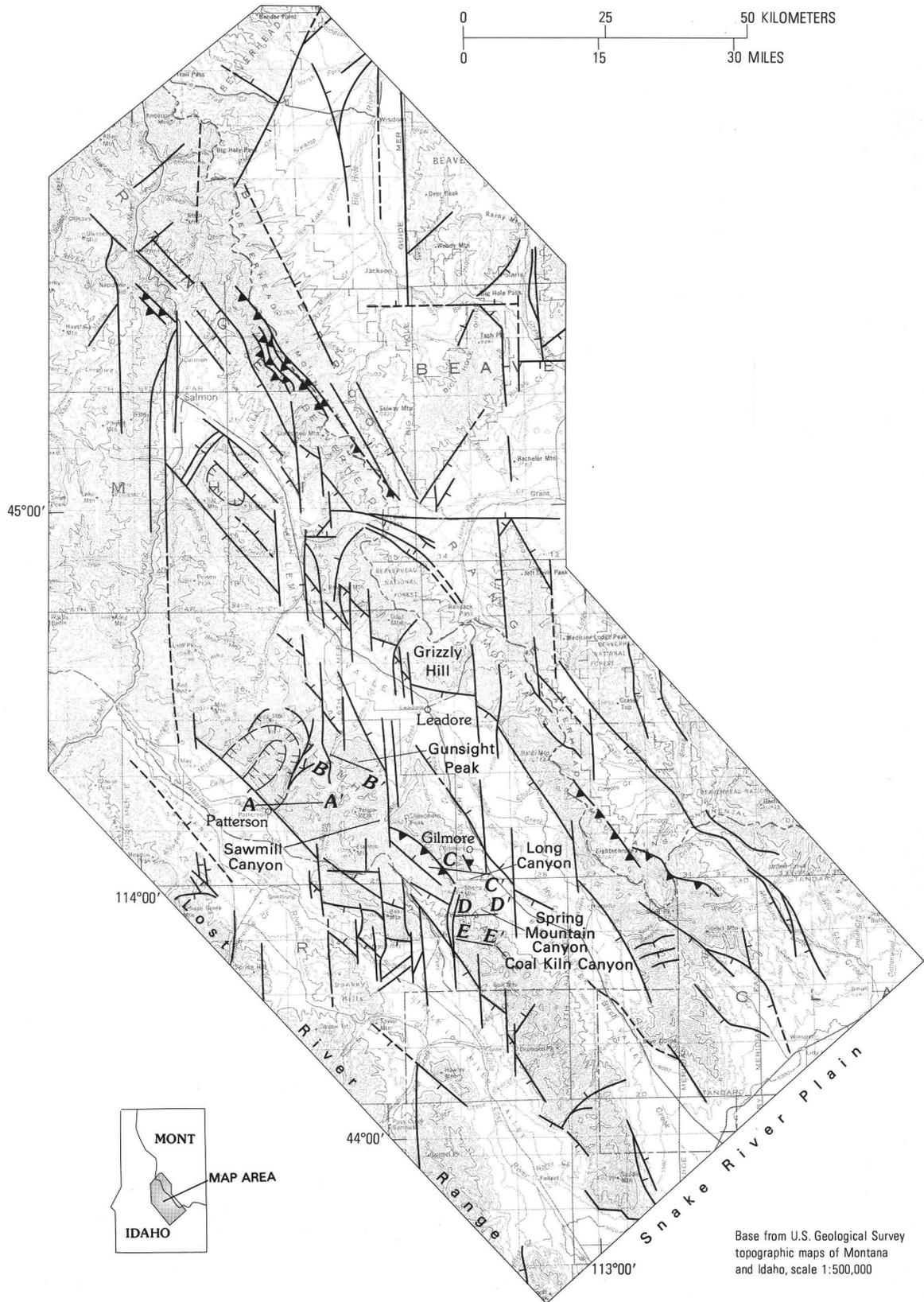
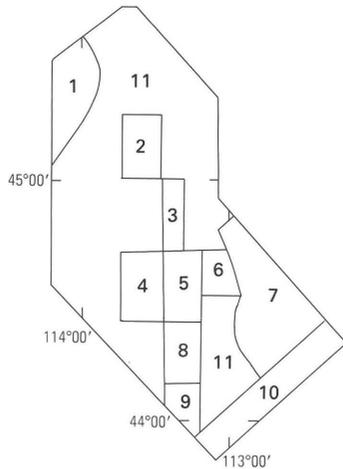


FIGURE 3 (above and facing page).—Major steep faults in the Lemhi Range and Beaverhead Mountains, east-central Idaho and southwest Montana.

EXPLANATION

-  Fault, steeply dipping, bar on downthrown side, although a few faults have late movement in opposite direction. Dashed where inferred
 Reverse fault, sawteeth on upthrown block. Dashed where inferred
 Caldera margin or ring-fracture zone
 A—A' Line of section shown in figure 4



INDEX OF PRINCIPAL SOURCES

Geology modified from:

1. David A. Lopez (oral commun., 1979)
2. Tucker (1975)
3. Staatz (1972, 1973)
4. Ruppel (1980)
5. Ruppel (1968)
6. Lucchitta (1966)
7. Scholten and others (1955), Scholten and Ramspott (1968)
8. Ruppel and Lopez (1981)
9. Mapel and Shropshire (1973)
10. Skipp and Hait (1977), Beutner (1968)
11. Ruppel (unpublished mapping)

northward along the top of the range and dip more steeply on the flanks of the range, which are broken by steep normal faults on both sides of the range (Tucker, 1975, p. 168–172; Coppinger, 1974, p. 181–185; Ruppel and Lopez, in press). East of Salmon, Idaho, the northwest-trending Miner Lake–Beaverhead Divide zone of reverse faults, dipping 70° or more west, parallels the range crest (fig. 3) (Tucker, 1975, p. 136–146; MacKenzie, 1949, p. 34–36; Ruppel, 1978, p. 8) and places allochthonous rocks of the Medicine Lodge and Grasshopper thrust plates on the east against autochthonous rocks of the Yellowjacket Formation on the west. However, the fault zone originated in the Precambrian as a normal fault, and only the Cenozoic movement is reverse (Ruppel and Lopez, in press). Thin

erosional remnants of the Medicine Lodge plate overlie the Yellowjacket Formation on the west side of the range, and dip westward as much as 25° . The east side of the Beaverhead Mountains in this region has not been mapped, but some imbricate thrust slices high in the range are known to dip eastward, commonly at 10° or so.

INTERPRETATION

The folds and steep faults in the Lemhi Range and Beaverhead Mountains have been attributed in earlier reports to episodes of compression and extension in the upper crust, and the regional structural elements have been thought of as more or less simple, broad anticlines and synclines, broken by basin-range normal faults and by a few steep reverse faults whose origin remained enigmatic. But the “anticlines” that form the ranges actually are flat-topped and have monoclinical flanks that are broken by normal faults almost everywhere and by known steep reverse faults in a few places (fig. 4, sec. *F–F'*). The tilted limbs of the monoclinical folds commonly dip 20° – 60° into the adjacent valleys but in some places are nearly vertical. The structural configuration suggests that the linear mountain ranges of east-central Idaho are complex block uplifts in which the earlier thrust-faulted sedimentary rocks of the region have been folded, more or less passively, over vertically rising basement blocks. The structurally flat, central parts of the mountain blocks are thus interpreted as being above the central parts of uplifted basement blocks. The monoclinical folds are interpreted as drape folds over the edges of rising basement blocks, a folding process facilitated by the multiple slip surfaces in imbricate thrust faults and by the thick Medicine Lodge decollement, as well as by slip between beds and within shaly formations. (See Stearns, 1978, p. 22–30.) The few major reverse faults of the region are interpreted as shallow extensions of reverse faults bounding the basement blocks, that continue into the overlying veneer of sedimentary rocks. These faults are known (fig. 3) along the east flank of the southern Beaverhead Mountains, where the sedimentary veneer is thin; in the Miner Lake–Beaverhead Divide reverse fault zone, in the northern part of the Beaverhead Mountains, the faults are known where Cenozoic reverse movement occurred along a Precambrian fault zone; and the reverse faults are known south of Gilmore, some of which appear to be local features, perhaps formed by local stresses during folding (fig. 4, sec. *C–C'*) (Prucha and others, 1965, p. 991).

The Patterson ring-fracture complex and the Withington Creek caldera are both on the edges of the Lemhi Range in positions that suggest that basement fractures could have controlled the location and development of these Challis calderas, before major block uplift. The

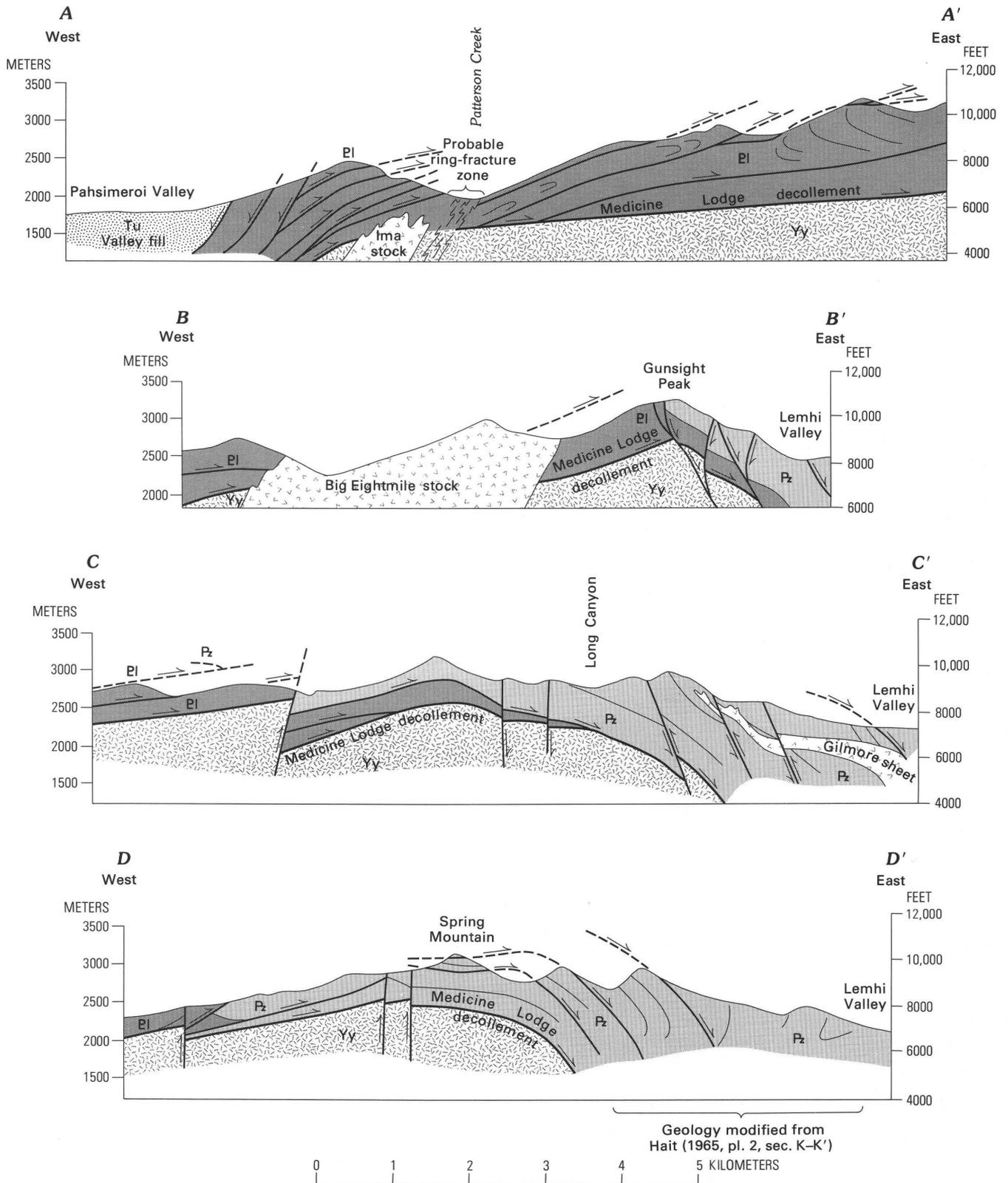
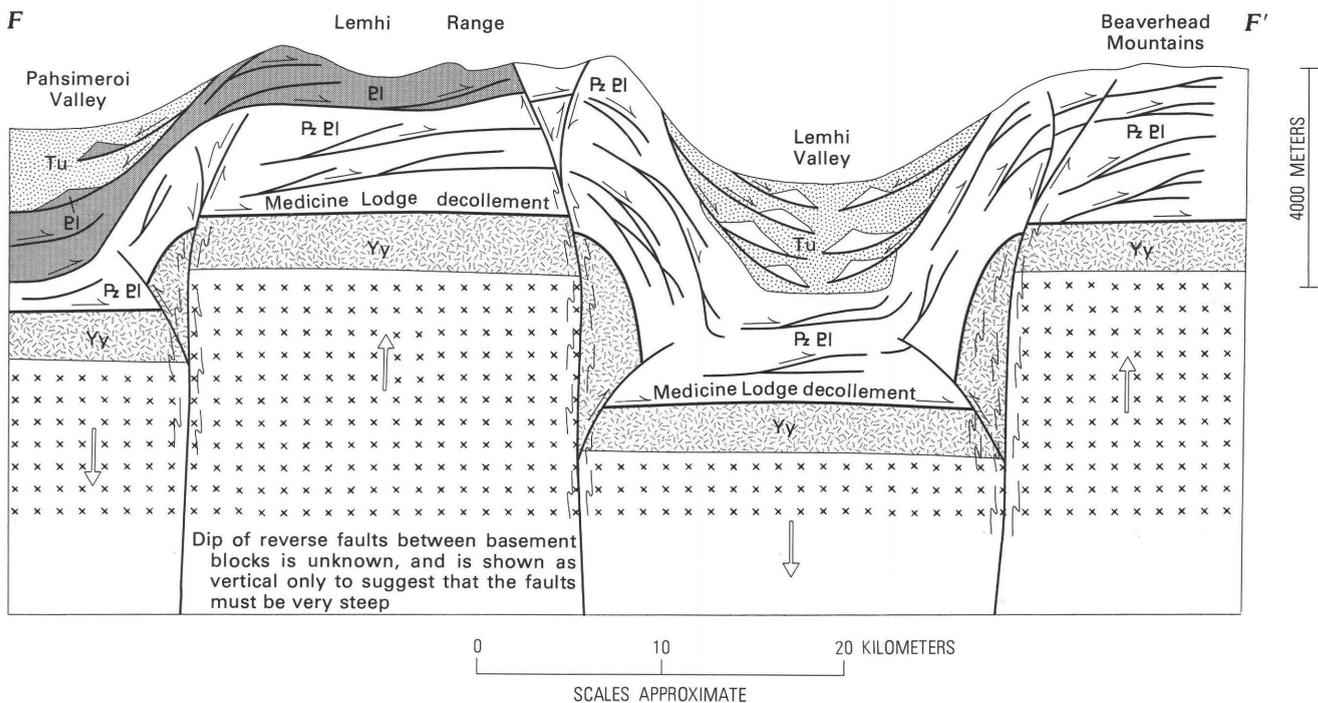
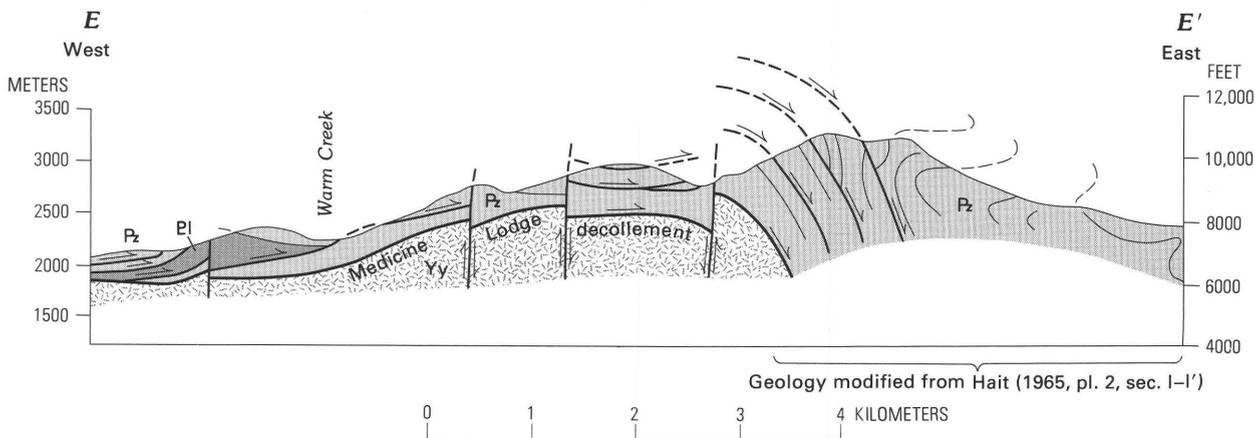


FIGURE 4.—Structural cross sections of the central part of the Lemhi Range, Idaho. A-A', across the west-dipping monoclinical west flank the Gilmore area; C-C', Long Canyon; D-D', Spring Mountain Canyon; E-E', Warm Creek to Coal



EXPLANATION

- | | |
|--|--|
| <ul style="list-style-type: none"> Tuff and gravel in valley fill of Tertiary age Paleozoic sedimentary rocks in Medicine Lodge thrust plate Proterozoic sedimentary rocks in Medicine Lodge thrust plate Paleozoic and Precambrian sedimentary rocks in imbricate thrust slices in Medicine Lodge thrust plate (sec. F-F' only) Proterozoic sedimentary rocks of Yellowjacket Formation, beneath Medicine Lodge thrust plate Granodiorite and quartz monzonite stocks and sheets of Tertiary age Precambrian basement crystalline metamorphic rocks (sec. F-F' only); arrows show inferred differential displacement of fault-bounded basement blocks | <ul style="list-style-type: none"> Contact or bedding Medicine Lodge decollement Imbricate thrust faults in Medicine Lodge plate Reverse fault Normal fault Strike-slip fault; arrows show relative displacement |
|--|--|
- Sources: Sections A-A', and B-B', Ruppel (1980); sections C-C', D-D', E-E' Ruppel and Lopez (1981); D-D', Hait (1965).

near Patterson. B-B', across the east-dipping monoclinial east flank near Gunsight Peak. Across the east-dipping monoclinial east flank in Kiln Canyon. F-F', Composite schematic section across the Lemhi Range and Lemhi Valley.

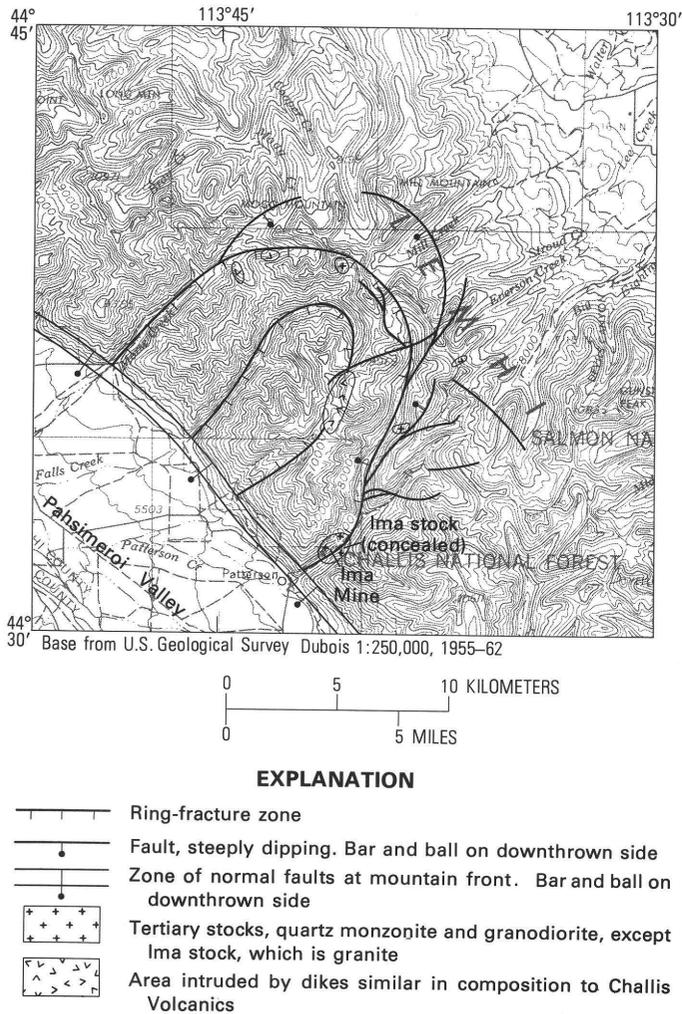


FIGURE 5.—Sketch map of ring-fracture complex in the Lemhi Range north of Patterson, Idaho.

elongate, oval shape of the Patterson ring-fracture complex (fig. 5) suggests that it might have been stretched. If it originally was more nearly circular, as the curving faults and curving canyons imply, the present elongate shape could be a result of stretching over the edge of a rising block of basement crystalline rock.

Most of the normal faults along the mountain fronts appear to be relatively minor faults, which outline and emphasize the mountain blocks, but which are secondary structures formed by gravitational collapse of the monoclinical shoulders of uplifted blocks into adjacent basins. Some gravitational sliding probably accompanied the early stages of block uplift, as older thrust faults were steepened by monoclinical folding along the range flanks, and provided readymade slip surfaces for gravity sliding. As uplift continued, the thrust surfaces were progressively steepened, and so made more un-

stable, and other, normal faults formed as the monoclinical shoulder was raised higher and masses of increasingly unsupported rocks failed and slid into the adjacent basins. Gravitational collapse of unsupported monoclinical block shoulders seems likely to have contributed significantly to denudation of the uplifted blocks, to stripping of earlier Tertiary Challis Volcanics from the ranges, and to filling of the adjacent basins. The young normal faulting marked by conspicuous scarps on the southwest sides of the block uplifts, and strike-slip faulting, reflect movements during regional warping later than the main block uplift. These movements discussed in more detail later in this report (p. 16-17).

In summary, the linear, northwest-trending mountain ranges of east-central Idaho appear to be block uplifts, composed of drape-folded sedimentary rocks above still-concealed blocks of basement crystalline rocks that have been vertically uplifted. Monoclinical drape folds, modified by secondary normal faults, form the flanks of each mountain range, and they more or less outline the shapes of the underlying basement blocks, which suggests that the basement blocks are bounded mainly by northwest- and east-trending reverse faults. The northwest-trending reverse faults in a few places reach up into the drape folds. The region is thus inferred to be one of flat-topped uplifts and flat-bottomed basins, separated by monoclinical folds and minor, secondary normal faults; this is in contrast to the conclusions of some earlier reports that the ranges owe their origin to basin-range normal faulting. The youngest normal faults and strike-slip faults suggest a small amount of block tilting related to late regional warping, rather than to the block uplifts that formed the ranges.

AGE OF BLOCK UPLIFTS

The time of major block uplifts in east-central Idaho and in southwestern Montana west of the edge of the thrust belt can be fixed only within rather broad limits. A maximum age is indicated by the time that thrust faulting was completed, about 76 m.y. ago (Ruppel and Lopez, in press), because the thrust faults are folded over the uplifted blocks. A still younger age is suggested by relations of Challis Volcanics of Eocene age, for these rocks commonly are folded at the mountain fronts and dip steeply into the valleys, and the volcanics are broken by normal faults at the range fronts (Ruppel, 1968, 1980; Ruppel and Lopez, 1981).

A late Tertiary, perhaps Miocene age for the major uplift in east-central Idaho seems most likely. A. L. Anderson (1961, p. 71) concluded that uplift of the ranges near Salmon, Idaho, might have begun in very late Oligocene time and continued through the Miocene,

with relatively little uplift since then. Major mid-Miocene uplift is suggested by abundant coarse, locally derived conglomerate beds in mid-Miocene tuffs (Nichols, 1975) in the upper part of the Lemhi Valley, and some of the normal faults on the east side of the Lemhi Range have been inactive at least since the late Pliocene (Ruppel, 1964, p. C16; 1967, p. 657-658), suggesting major uplift from mid-Miocene to middle or late Pliocene. An about similar span of faulting, but mainly Miocene, was suggested by Scholten, Keenmon, and Kupsch (1955, p. 396-398) and Scholten and Ramspott (1968, p. 34-38, 53) for the southern Beaverhead Mountains. None of these estimates for the age of major uplift is definitive, and starting and ending points are not well known. The available evidence suggests, however, that most uplift took place in Miocene time, but that uplift may have started in late Oligocene time and may have continued to middle Pliocene time.

The latest movement on northwest-trending normal faults in east-central Idaho, partly marked by very young scarps cutting all but the youngest alluvial deposits, is almost all along the southwest sides of the uplifted blocks. North-trending strike-slip faults of similar age occur on both sides of uplifted blocks, where the range-trends zigzag from northwest to east-west, and back to northwest. These youngest movements probably started in the late Pliocene and have continued almost to the present (Ruppel, 1964, p. C16; 1967, p. 658).

RELATIONS OF BLOCK UPLIFTS IN EAST-CENTRAL IDAHO AND SOUTHWEST MONTANA

The block uplifts of the cratonic region in southwest Montana, and those farther west in Montana and east-central Idaho, are similar in most respects. Throughout the region, the uplifts trend in generally similar directions and are parallel to faults and structural trends formed in Precambrian time. The exposed basement blocks in the eastern part of the region are at least partly bounded by Precambrian faults that moved recurrently in Late Cretaceous and Cenozoic time. By inference, the basement blocks beneath the more linear uplifts of east-central Idaho also are bounded by Precambrian faults, and the pattern of the ranges suggests that the dominant bounding faults at depth must trend northwest and east—the same directions as those of demonstrable Precambrian faults farther east. Drape folding accompanied uplift of blocks in both southwest Montana and east-central Idaho, as did reverse faulting and subsequent normal faulting on the mountain flanks, and as did gravitational sliding of rocks from the top and sides of the uplifts (Tysdal, 1970, p. 124-129). The time of ma-

major uplift is the same throughout the region—with perhaps some uplift in the late Oligocene, with major uplift in the Miocene probably continuing into the Pliocene, and with conspicuous but relatively minor uplift or block tilting from late Pliocene to the present (Klepper, 1950, p. 75-76; Pardee, 1950, p. 366-367; Tysdal, 1970, p. 105-130; Dorr and Wheeler, 1964, p. 328-335).

The differences between the block uplifts seem to be more apparent than real. The reverse faults that commonly bound and cut the crystalline basement cores of the eastern uplifts are not evident farther west, where only a few reverse faults are known. The difference probably is a consequence of the difference in thickness of the sedimentary veneer above the basement blocks. Little veneer is left on the eastern block uplifts, and the uplifts are exposed to a much deeper structural level than the uplifts to the west, where the veneer, originally greatly thickened by major thrust plates, is still many thousands of meters thick and no crystalline cores are exposed. The basement reverse faults inferred to be present at depth, beneath the western block uplifts, probably die out upward in the thick sedimentary veneer (for example, Stearns, 1971, p. 128-132); they are suggested, however, by the few known major reverse faults (figs. 3, 4), and especially by the Miner Lake-Beaverhead Divide fault zone.

The initial uplift of the eastern blocks was in Late Cretaceous time (Klepper, 1950, p. 74), when northeast-trending domes rose in a foreland bulge in front of the thrust belt (fig. 6) (Ruppel and Lopez, in press). These initial domes differ in trend and magnitude from the Tertiary block uplifts, and they differ in being closely related to thrust faulting. The main block uplifting, throughout the region, was mostly in a Miocene time and is distinct from the earlier, Cretaceous uplifts.

YOUNG FAULT SCARPS AND THE DEBATE ON BASIN-RANGES IN EAST-CENTRAL IDAHO

Brief discussions or assertions on the origin of the linear mountain ranges of east-central Idaho have been a part of almost all reports on the geology of different areas in the region, and a debate of sorts has limped along almost from the time the ranges were first described as products of regional uplift and erosion (Umpleby, 1913, p. 48-49). As earlier summarized (p. 3), Meinzer (1924, p. 15) first recognized normal faults on the flanks of the ranges, and subsequent reports by others have yielded almost as many interpretations as there are reports: as thrust-bounded wedge uplifts (Kirkham, 1927, p. 27-29); as tilted fault blocks (R. A. Anderson, 1948; Baldwin,

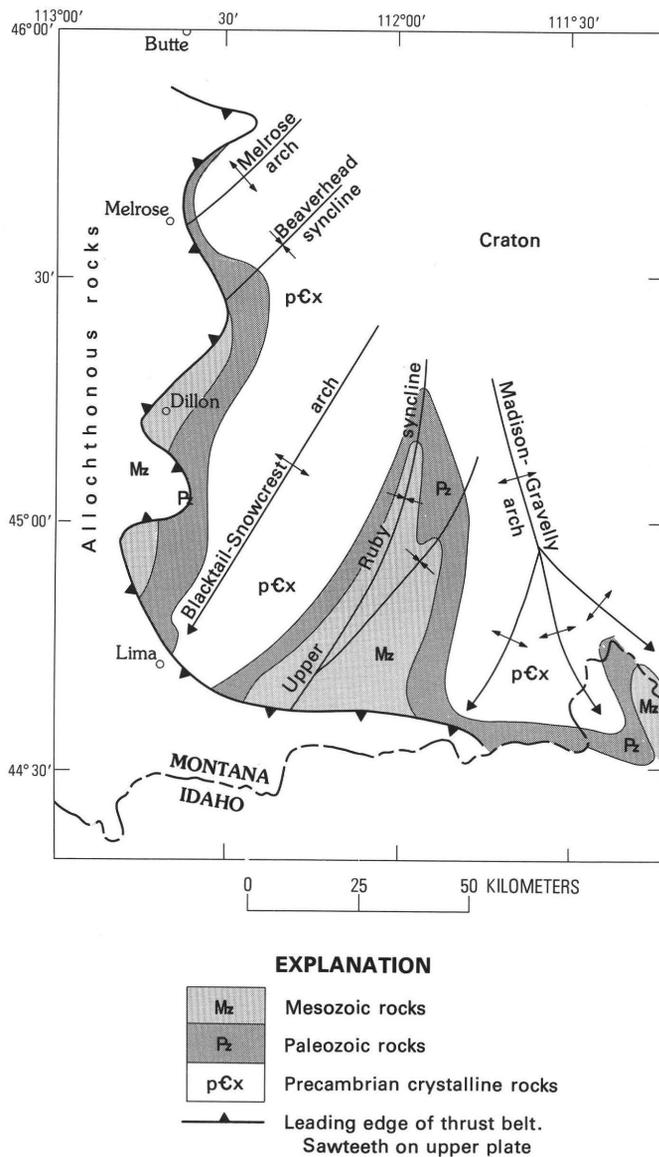


FIGURE 6.—Domes and basins in southwest Montana in Late Cretaceous and early Tertiary time, before major uplift of mountain blocks in Miocene time (modified from Scholten, 1967, fig. 3).

1951; Skipp and Hait, 1977, p. 499, 509); as folded belts (Ross, 1961, p. 236; and earlier reports); as fault-bounded basin-ranges (Shanon, 1928, p. 5; Ruppel, 1964, p. C16); and, in the present report, as drape-folded block uplifts flanked by minor, secondary normal faults that are slip surfaces of gravitational slide sheets. My conclusion, that the ranges are block uplifts, suggests that Kirkham (1927, p. 27–29), who proposed the wedge uplift interpretation, was more nearly correct than most of his successors, but neither the wedge uplift nor folded belt interpretations survived for long, because steep, normal faults clearly do exist in many places along the range fronts. The debate has centered until now on the basin-

range and tilted fault-block interpretations and has been based almost entirely on evidence drawn from the southern parts of the Lemhi Range and Beaverhead Mountains. These are areas where young normal fault scarps are conspicuous on the southwest sides of the ranges, and the differing interpretations of the ranges are based largely on differing interpretations of the significance of the young faults.

The debate has had several interrelated parts: (1) are the ranges bounded by faults on both sides, or on only one side; (2) what is the evidence for block tilting, and is it valid; and (3) when did uplift, tilting, or both take place? The first two parts are closely related. The most obvious normal faults are those marked by young scarps on the southwest sides of all the linear ranges in east-central Idaho. No similar young faults have been mapped on the northeast sides of the southern Lemhi and Lost River Ranges, and so the ranges were interpreted to be tilted blocks. No other evidence for block tilting has been advanced. However, the Beaverhead Mountains are outlined by nearly continuous faults on both sides (fig. 3), as are the central and northern parts of the Lemhi Range. At Gilmore, on the east-central side of the Lemhi Range, the principal normal fault is several kilometers east of the mountain front; the fault is beveled by a pediment and is partly concealed by a veneer of pediment and glacial gravels (Ruppel and others, 1970, p. 16–17). Gravity studies (Kinoshita and others, 1969) show, too, that the valleys are symmetrical and deepest in the middle, and not deepest along the southwest-facing scarpline as would be true if they were on the back slope of an eastward-tilted fault block. And finally, the Medicine Lodge decollement and related imbricate thrust faults above it are nearly flat or dip gently west in the inner parts of the Lemhi Range and Beaverhead Mountains, but they should dip at least moderately and consistently to the east if the ranges were tilted fault blocks uplifted thousands of meters on the west. The available evidence thus indicates that the uplifts of east-central Idaho are symmetrical, two-sided, and not significantly tilted whether or not they are bounded by normal faults on both sides and suggests that some normal faults might be away from the mountain front, as at Gilmore, and hidden by Pliocene and Pleistocene gravels.

The explanation for the young faults on the southwest sides of the Idaho ranges is partly to be found in the third element of the basin-range debate—when did uplift, tilting, or both take place? As earlier discussed, block uplift was mostly in Miocene time and was essentially vertical because the blocks are not significantly tilted. The movement that produced the young fault scarps on the southwest sides of the Idaho ranges probably began in the late Pliocene and continued into the Holocene (Ruppel, 1964, p. C16; 1967; Hait and Scott, 1978).

The young fault scarps in Idaho are paralleled in southwest Montana by similarly young, but mostly northeast-facing fault scarps (Pardee, 1950, p. 403-404; Scholten, 1968, p. 118-119).

The late Pliocene to Holocene normal faulting reflected in the young fault scarps was accompanied by the rise of northeast-trending arches north of and parallel to the Snake River Plain (fig. 7) (Kirkham, 1927, p. 11; Ruppel, 1967). The concordance in timing suggests a relation in origin. The best known arch, just north of the Snake River Plain, is an elongate, northeast-trending dome, that, in its uplift, divided the earlier southeast-draining intermontane basins of the region and reversed the drainage in the northern parts of the basins, so that the present rivers north of the arch flow to the northwest. (See Ruppel, 1967.) The highest part of the arch lies on the Montana-Idaho boundary and separates the region of the southwest-facing scarps in Idaho, from the region of northeast-facing scarps in Montana. The scarps mostly are at high angles to the long axis of the dome, a relation that suggests that they reflect extensional movements away from the crest of the dome, or, put another way, that they reflect stretching parallel to the long axis of the dome. The extension does suggest some rotation of the mountain blocks, not related to the original block uplift, but the rotation is so slight as to be undetectable except in the young faults. Some indication of the amount of rotation is suggested by the apparent total displacements on young fault systems: at Patterson, on the west side of the Lemhi Range, the young faults have an aggregate displacement of about 100-150 m, judging from reconstruction of pre-fault stream courses. On similar evidence, the young faults north of Leadore, on the west side of the Beaverhead Mountains, have a total vertical displacement of about 60 m (fig. 8) (Ruppel, 1964, p. C16). Reverse displacement on the fault near Gilmore, on the east side of the Lemhi Range, is about 120 m (Ruppel, 1964, p. C16; Ruppel and others, 1970, p. 17) and suggests that the entire Lemhi Range block rotated up on the southwest and down on the northeast by about the same amount—a little more than 100 m, in late Pliocene through Holocene time.

STRIKE-SLIP FAULTS

Vertical, north-trending strike-slip faults are widely distributed in east-central Idaho and the adjacent part of southwest Montana (fig. 3) (Ruppel, 1964), although just how widely is still in some dispute (Beutner, 1968, p. 54; Skipp and Hait, 1977, p. 499). The faults are concentrated in those areas where the ranges change trend from northwest to east. The latest movements along the faults are Pliocene through Holocene, but some earlier movements, not clearly recognizable now, seem likely. A

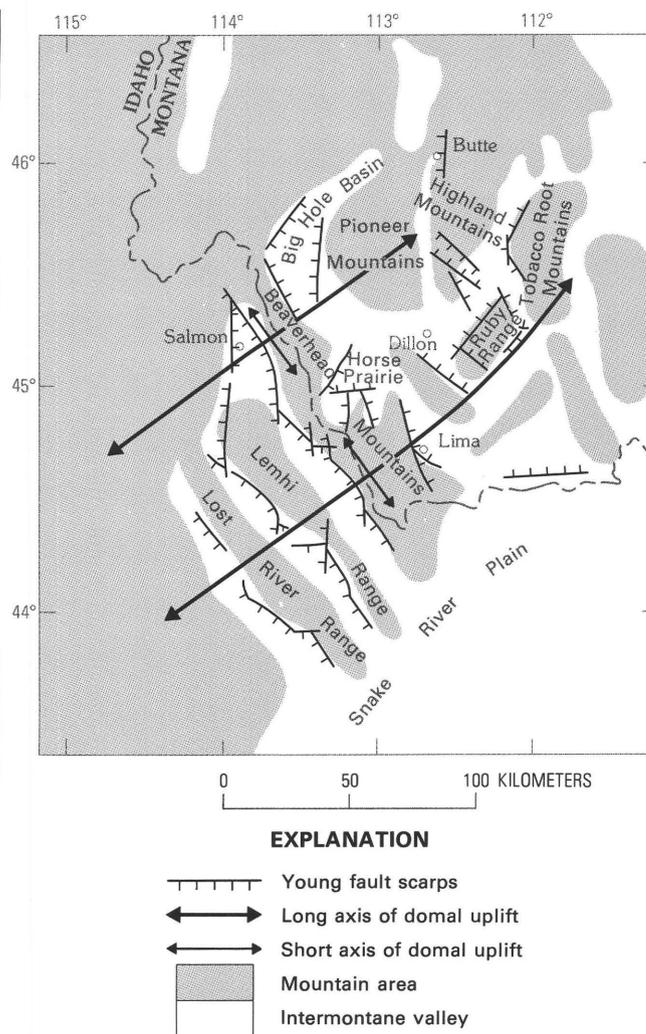


FIGURE 7.—Map showing the effects of Pliocene to Holocene arching and faulting north of the Snake River Plain, Montana-Idaho.

satisfactory explanation for the faults remains elusive (Ruppel, 1964, p. C18; Scholten and Ramspott, 1968, p. 47), but their locations, where block uplifts change trend, suggest that they are tear faults in the sedimentary veneer above different basement blocks that moved or tilted differentially.

NORTHEAST-TRENDING LINEAMENTS

East-central Idaho and southwest Montana are crossed by broad, northeast-trending bands of different rocks, separated by lineaments that coincide in places with known faults (fig. 9), and which also suggest basement structural controls (Hyndman and others, 1977). The lineaments are conspicuous on space imagery of this

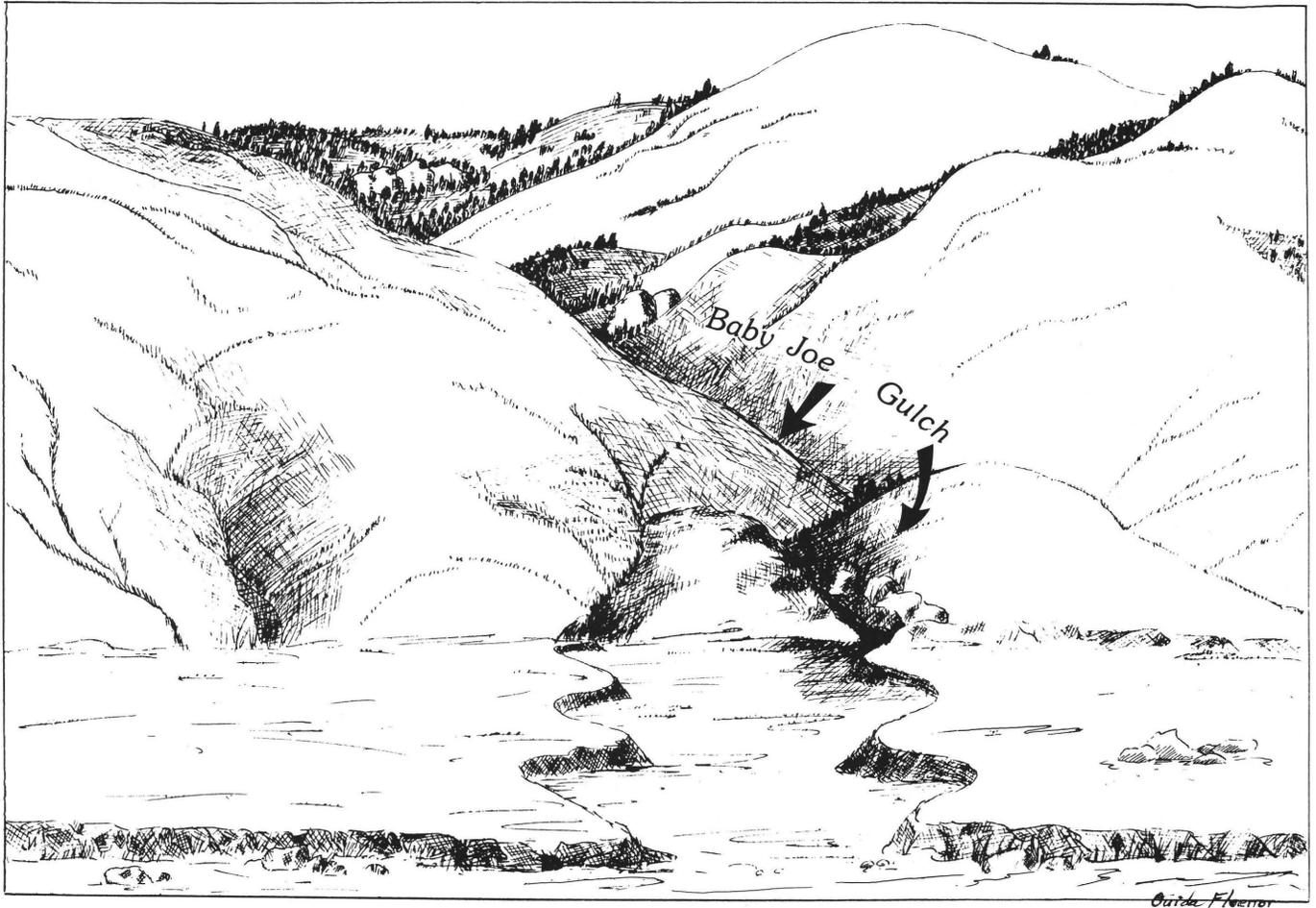


FIGURE 8.—The faulted course of Baby Joe Gulch, north of Leadore, Idaho, looking north. The stream course in the foreground is several hundred meters wide but is cut off by young faults along which uplift has taken place at the mountain front; Baby Joe Gulch is the narrow, V-shaped gulch entering the stream course on the right.

Upstream about 300 m, and behind the two sharp bends in the gulch, Baby Joe Gulch widens to fit the down-faulted segment of its original channel. The vertical displacement between the faulted segments of the original channel is about 60 m. Sketch by Ouida B. Fleenor.

region. The southernmost lineament is the northwest edge of the Snake River Plain, separating the volcanic rocks of the plain from the mainly Paleozoic sedimentary rocks to the north. No faults are known along the lineament (M. L. Kuntz, oral commun., 1979). The middle lineament extends across the north end of the linear ranges of east-central Idaho into Horse Prairie in southwest Montana, and farther northeast along the southeast side of the Highland Mountains. The lineament coincides with a known steep fault in the head of Horse Prairie and a possible fault along the Highland Mountains, an area not mapped. It separates the region of Paleozoic and Proterozoic Y sedimentary rocks on the south from one to the north that is underlain mostly by Tertiary Challis Volcanics and older Proterozoic Y sedimentary rocks, but which includes younger Paleozoic and Mesozoic sedimentary rocks and the

Boulder batholith at its east end in Montana. The northernmost lineament, described by Hyndman, Badley, and Rebal (1977), trends northeast through an area of northeast-trending faults near Gibbonsville, Idaho, to the northwest side of the Big Hole Basin in Montana, a part of the basin that is bounded by a northeast-trending fault. The region north of this lineament is composed dominantly of batholithic rocks. The lineament, extended, falls more or less on the west side of the Boulder batholith.

The lineaments are crossed by many of the faults of this region, with no apparent effect, but nonetheless they seem to outline regions of somewhat different overall structure, as well as of different rocks. The region immediately north of the Snake River Plain encompasses most of the known block uplifts in east-central Idaho and southwest Montana, although both the Lemhi Range

and Beaverhead Mountains extend beyond it to the northwest. Most of the known major faults farther northwest trend northeast, at right angles to the dominant northwest trend in the region north of the Snake River Plain, but northwest-trending block uplifts, not as obvious, probably are present as well. The northwest region also includes the northeast-trending dike swarms described by Hyndman, Badley, and Rebal (1977).

The lineament-bounded regions seem to confine the elongate domes that rose in late Tertiary and Quaternary time (p. 17) and so seem to have influenced the late Cenozoic regional uplifts north of the Snake River Plain.

The lineaments are so dimly seen, and the structure of some of the region so poorly known, that their origin is uncertain. The most prominent faults along them are in the oldest, and so the deepest rocks, and these oldest rocks also are partly covered by abundant volcanic rocks and are intruded by dike swarms parallel to the linea-

ments. The relations suggest that the lineaments reflect deeply buried major fractures in the underlying crystalline basement, as Hyndman, Badley, and Rebal suggested (1977). If so, the fractures seem most likely to have originated in Precambrian time.

THE RELATION OF INTRUSIVE IGNEOUS ROCKS AND ASSOCIATED MINERAL DEPOSITS TO EDGES OF UPLIFTED BLOCKS

The principal known deposits of metallic minerals in east-central Idaho are almost all near the margins of the mountain ranges and so are on the monoclinical flanks of uplifted mountain blocks (fig. 10). The distribution of these mineral deposits and of associated quartz monzonite and granodioritic intrusives was discussed in an earlier report (Ruppel, 1978, p. 4-5; 18-20), in which I concluded that the Medicine Lodge thrust system had restricted the upward movement of intrusive magmas and mineralizing solutions to the lower part of the thrust plate. The geologic relations of some of the intrusive bodies now are better known and show that some of the intrusive masses are not stocks, but rather that they are sheets intruded into thrust faults.

In the central part of the Lemhi Range, all of the principal mineral deposits are associated with stocks on the mountain-block flanks, and only a few smaller deposits are associated with sheets of igneous rock. The relation of stocks, sheets, and mineral deposits is most evident in the Gilmore mining district (fig. 10) (Ruppel and others, 1970; Ruppel and Lopez, 1981), for only the central part of the Gilmore intrusive mass seems to be truly a stock, and the most productive mineral deposits are in a small area adjacent to this part of the intrusive. The north part of the intrusive is a thick, short sill, intruded into the lower part of the Devonian Jefferson Formation, with only a few associated deposits of metallic minerals. The south part of the intrusive is a thick sheet intruded into one or more thrust faults that extends about 10 km southward from Gilmore to Spring Mountain Canyon. Only small deposits of metallic minerals have been found in the sedimentary rocks enclosing the sheet, and none of them have yielded appreciable amounts of ore. The relations of igneous rocks and associated mineral deposits around the Gilmore stock and its peripheral sheets suggest that the stock was the main intrusive center and the main center for mineralization. The sheets were fed from the stock and are fairly simple intrusive masses that did not carry significant mineralizing solutions. Perhaps their main importance is in showing that magma spread laterally into the lower part of

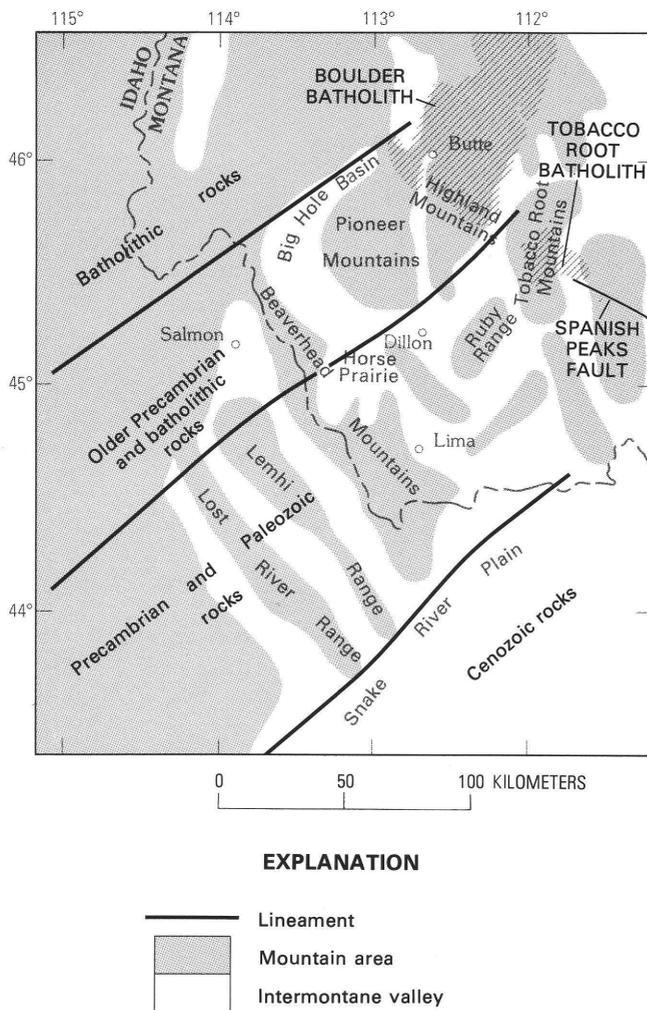


FIGURE 9.—Northeast-trending lineaments in east-central Idaho and southwest Montana.

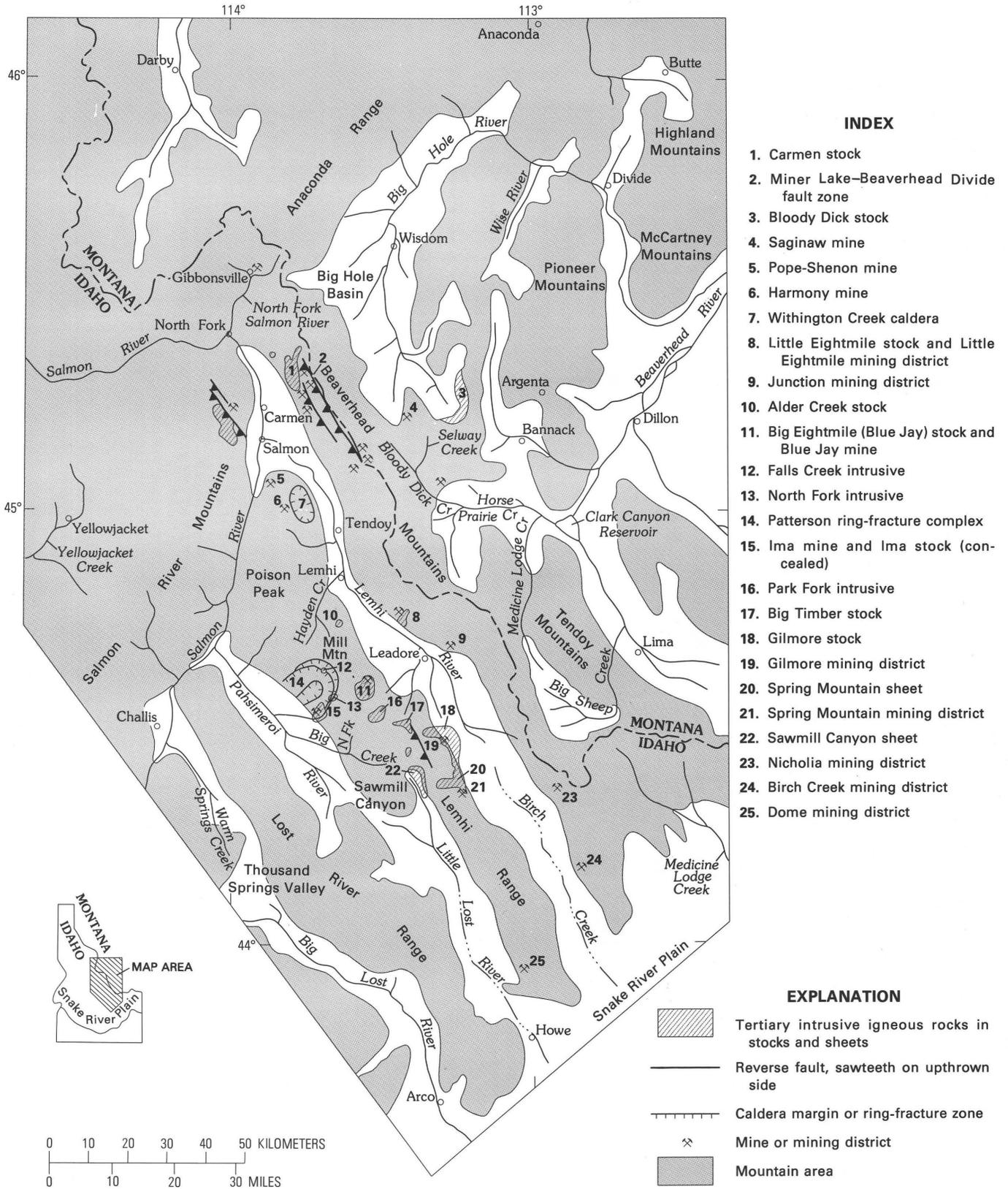


FIGURE 10.—Map showing distribution of Tertiary intrusive rocks and mineral deposits in east-central Idaho.

the Medicine Lodge thrust plate, mostly as sheets intruding imbricate thrusts. The abundance of imbricate thrusts in the Medicine Lodge plate, and so of available avenues for lateral spread of magma, restricted intrusive activity to the lower part of the plate and seems to explain why quartz monzonite-granodiorite stocks and sheets—and associated mineral deposits—are only found low in the thrust plate.

Only a few of the other intrusive masses in the Lemhi Range seem clearly to be stocks. The largest of these is the Big Eightmile stock, which is a crosscutting composite intrusive suggesting repeated intrusive pulses. The core of the Big Eightmile stock is hydrothermally altered and contains disseminated pyrite, chalcopyrite, and some molybdenite. Only a few small vein deposits of lead and silver minerals are known around the Big Eightmile stock, probably because the enclosing quartzitic rocks were not as favorable a host for replacement as were the sandy carbonate rocks of the lower part of the Jefferson Formation that contain the major ore bodies at Gilmore (Ruppel and others, 1970, p. 19-23; Umpleby, 1913, p. 63-69, 89-109). The Big Timber stock intrudes a steep reverse fault and is probably truly a stock, but its westward extensions are sheets or sills (Ruppel and Lopez, 1981; Ruppel, 1968). No mineral deposits are known around it. The Ima intrusive mass, at Patterson, is not exposed at the surface, but the results of exploration studies for deposits of associated tungsten and molybdenum minerals suggests that it is a stock; it and two small stocks farther north (fig. 5) probably were intruded in a ring-fracture zone (p. 9.).

Other intrusive masses in the Lemhi Range are characterized by nearly flat roofs, and occur in or near imbricate thrust faults, a relation that suggests that they are sheets. The largest of these is the Sawmill Canyon sheet, whose intrusive center is probably concealed by glacial deposits; a few small deposits of lead-silver minerals and a barite deposit are known in the host rocks above the sheet. The intrusive mass in the Park Fork of Big Creek probably is also a sheet, perhaps fed from the Big Timber stock. The other intrusives in the Lemhi Range are small, semiconcordant bodies roofed in thrust faults, and most of them probably are small sheets.

Small deposits of metallic minerals are widely distributed along the west flank of the Beaverhead Mountains (fig. 10), but only the deposits in the central and northern parts of the range are associated with exposed intrusive igneous rocks—the Little Eightmile and Carmen stocks (Staatz, 1972, 1973; MacKenzie, 1949, p. 15-21; A. L. Anderson, 1959, p. 33-40). The map pattern of the southern part of the Little Eightmile stock (Staatz, 1973) suggests that it is a sheet intruding a thrust fault. The Carmen stock is a compound,

inclusion-rich granodiorite that probably does not have any peripheral sheets; but it has not been studied in much detail and its contact relations are only partly known (MacKenzie, 1949; A. L. Anderson, 1957, 1959). Small deposits of gold, and of copper, lead, silver, and tungsten minerals, are also distributed along the crest of the northern Beaverhead Mountains; most of them are near the Beaverhead Divide-Miner Lake reverse fault zone and are associated with dioritic dikes in and near the fault zone.

Gold deposits on the east slope of the Salmon River Mountains, west of Salmon, Idaho (fig. 10) are associated with a quartz monzonite stock (A. L. Anderson, 1956, p. 39-42; 1959, p. 37-40, 73-75) that apparently was intruded along a northwest-trending steep reverse fault.

The fairly consistent relation in east-central Idaho of stocks and associated mineral deposits on the flanks of mountain ranges, and along reverse faults in some places, suggests that the structures that are inferred to control the block uplifts in this region also controlled the emplacement of stocks and mineral deposits. I think that the controlling structures are steep reverse faults that bound uplifted blocks of crystalline rocks at depth, and I suggest that these faults were primary avenues utilized by magma rising from deep in the crust. The magma spread laterally into imbricate thrusts near the bottom of the Medicine Lodge thrust plate, to form sheets like those exposed in the central part of the Lemhi Range. The major mineral deposits of the region were deposited around and above necklike, central stocks that fed the sheets. Small deposits of metallic minerals occur in many places around the sheets, but they have yielded relatively little ore. The search for new mineral deposits, therefore, might be concentrated most usefully in areas known or inferred to be above the edges of buried crystalline blocks, where conduits in reverse faults, now stocks, have channeled rising magma to the base of regional thrust plates and there fed laterally spreading sheets. Substantial ore bodies have not been found and are not likely to have formed in the structurally flat central parts of the block uplifts, because the seemingly necessary deep structural controls are not present there.

The ring-fracture complex at Patterson and the Withington Creek caldera are on the edges of the Lemhi Range, and their location suggests that Tertiary centers of volcanism also were fed by magma rising along the reverse faults at depth.

The structural framework of southwest Montana is similar in most respects to that of east-central Idaho, and the primary structural controls on the emplacement of intrusive igneous rocks and deposition of associated mineral deposits probably are also similar.

SUMMARY AND CONCLUSIONS

The northwest-trending linear mountain ranges of east-central Idaho traditionally have been considered to be basin ranges bounded on one or both sides by large normal faults, but they are better described as flat-topped block uplifts flanked by monoclinical folds. The normal faults that outline the present mountain ranges are relatively minor, secondary faults formed by gravitational collapse and sliding of sheets of rock from the steepened monoclinical limbs of the uplifts into the adjacent valleys. The mountains and valleys thus owe their structural relief not to normal faulting but to essentially vertical relative uplift of the mountain blocks. The normal faults suggest extensive gravitational denudation of sedimentary and volcanic rocks from the block uplifts, and the plates of denuded rocks must form a substantial part of the fill in the adjacent valleys.

The monoclinical folds on the flanks of the block uplifts are interpreted as drape folds, in which sedimentary rocks, earlier deformed by regional thrust faults, have been passively folded over the edges of deeper, rising blocks of crystalline rocks. The older, imbricate thrust faults seem likely to have provided multiple slip surfaces that made possible the abrupt draping of the sedimentary veneer over the crystalline blocks, and also provided at least some of the surfaces utilized by sheets of rock that slid from the steepened limbs into the valleys.

The block uplifts of east-central Idaho are similar to those east of the thrust belt in southwest Montana, and the apparent differences between the two regions are largely a result of eastward thrust faulting, which preceded major block uplift and carried a greatly deformed and thickened sequence of sedimentary rocks into east-central Idaho and part of southwest Montana. However, these apparent differences earlier led to a suggested division of the region into an eastern Laramide province of block uplifts and a western Sevier province of folded and thrust-faulted rocks cut by basin-range normal faults—a division that now seems to be only partly appropriate. In terms of post-thrusting Cenozoic tectonism, the region is a single structural province—one of flat-topped, basement-cored block uplifts with monoclinical, drape-folded flanks.

The block uplifts east of the thrust belt are cored by Precambrian crystalline metamorphic rocks, and the uplifts are in blocks defined partly by faults clearly of Precambrian age, but which have been the sites of recurrent movement almost to the present time. The northwest and east trends of Precambrian faults in southwest Montana are repeated in the trends of the block uplifts in east-central Idaho. The similarity of structural trends suggest that the Idaho uplifts, like those east of the thrust belt, are cored by crystalline metamorphic rocks in blocks defined by steep reverse

faults of Precambrian age. The crystalline block cores are not exposed in east-central Idaho, but a few steep reverse faults are present, and some of these like the large Miner Lake–Beaverhead Divide fault zone east of Salmon, Idaho, are probably shallow extensions of the still larger, steep reverse faults at depth. The development of calderas and the emplacement of intrusive igneous rocks and deposition of associated mineral deposits appear to have been controlled by the steep reverse faults between basement blocks, because the known calderas and the major stocks and mineral deposits are on the flanks of the block uplifts, above the inferred basement faults.

The block uplifts of east-central Idaho and southwest Montana suggest that Cenozoic faulting, folding, and mountain building is almost entirely a vertical response to forces acting on the bottom of basement blocks at great depth. The nature of the forces driving the basement blocks vertically is unknown. (But see Dickinson and Snyder, 1978; Sales, 1968; Stearns, 1971, 1978, p. 31–34.) The response of the rocks above the vertically and differentially rising basement blocks has been passive drape folding and gravitational sliding; there is no clear indication in the exposed rocks of the region of repeated episodes of compression and extension in the upper crust alternating through Cenozoic time.

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