Geothermal systems of the Corwin Springs-Gardiner area, Montana : possible structural and lithologic controls
by Eric Mitchell Struhsacker

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Earth Sciences
Montana State University
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Abstract:
This study is an attempt to determine by means of geologic observations the structural and lithologic controls on the circulation of geothermal waters in the La Duke and Bear Creek thermal spring systems. Hot spring activity has persisted in the Corwin Springs-Gardiner, Montana area since the Pleistocene. Presently the only active hot springs, La Duke and Bear Creek, emerge at opposite ends of a two square mile Pleistocene travertine deposit.

The hot springs and travertine lie along the northwest trending Gardiner fault, a Laramide high-angle reverse imbricate fault zone, which bounds the Beartooth crystalline rock uplift on the southwest.

The post-Laramade Reese Creek and Mammoth faults are graben-forming normal faults that extend from the Yellowstone Park upland, northward into the hanging wall of the Gardiner fault. The local thermal features lie on or between the intersections of these faults with the Gardiner fault zone.

More than 10,000 feet of Paleozoic and Mesozoic sedimentary rock are preserved within the graben in the footwall of the Gardiner fault. From a structural high within Yellowstone Park, the sedimentary units dip gently into the Gardiner fault zone, where they are dragged up and locally overturned to form an asymmetrical syncline striking northwest. These structural relationships suggest that meteoric waters flow down permeable sedimentary units within the graben from the Yellowstone upland to great depth under the Gardiner fault zone, thereby forming a common reservoir for the hot spring systems. The cavernous Mississippian Madison Limestone, lying near a depth of 10,000 feet under the Gardiner fault zone, may be the principal aquifer and produces the high Ca content of the active hot springs.

Waters are heated at depth by conduction from rocks whose temperatures depend on the geothermal gradient. They then ascend through fractures to the surfaced A normal thermal gradient for western Montana causes base temperatures near 100° C at this depth. However, the proximity of a shallow magma body beneath the Yellowstone Plateau to the south may accentuate the normal regional thermal gradient and produce higher base temperatures in the reservoirs.

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Date August 11, 1976

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by

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of the requirements for the degree

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Approved

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ABSTRACT

This study is an attempt to determine by means of geologic observations the structural and lithologic controls on the circulation of geothermal waters in the La Duke and Bear Creek thermal spring systems. Hot spring activity has persisted in the Corwin Springs-Gardiner, Montana area since the Pleistocene. Presently the only active hot springs, La Duke and Bear Creek, emerge at opposite ends of a two square mile Pleistocene travertine deposit.

The hot springs and travertine lie along the northwest trending Gardiner fault, a Laramide high-angle reverse-imbricate fault zone, which bounds the Beartooth crystalline rock uplift on the southwest. The post-Laramide Reese Creek and Mammoth faults are graben-forming normal faults that extend from the Yellowstone Park upland, northward into the hanging wall of the Gardiner fault. The local thermal features lie on or between the intersections of these faults with the Gardiner fault zone.

More than 10,000 feet of Paleozoic and Mesozoic sedimentary rock are preserved within the graben in the footwall of the Gardiner fault. From a structural high within Yellowstone Park, the sedimentary units dip gently into the Gardiner fault zone, where they are dragged up and locally overturned to form an asymmetrical syncline striking northwest. These structural relationships suggest that meteoric waters flow down permeable sedimentary units within the graben from the Yellowstone upland to great depth under the Gardiner fault zone, thereby forming a common reservoir for the hot spring systems. The cavernous Mississippian Madison Limestone, lying near a depth of 10,000 feet under the Gardiner fault zone, may be the principal aquifer and produces the high Ca content of the active hot springs.

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Chapter 1

INTRODUCTION

Geothermal phenomena have been intermittently active in the Corwin Springs-Gardiner area of southwestern Montana from the early Pleistocene to the present. Thermal springs have produced extensive travertine deposits up to 60 feet in thickness that extend for four miles from the vicinity of Little Trail Creek, northwest of Gardiner, to Bear Creek, east of Gardiner (Figure 1). Whereas most of the travertine was deposited before the last Pinedale glaciation, minor thermal spring activity continues on this trend at the Bear Creek warm spring (Plate 1) and at La Duke Hot Spring (Plate 2) (Fraser et al, 1969). Both springs are presently depositing moderate amounts of travertine. Base reservoir temperatures for La Duke Hot Spring are thought to range from 81^{o} C in the summer to 130^{o} C in the winter (Chadwick, personal communication, 1976).

These thermal features lie within the northwest trending Gardiner fault zone on the north side of the Yellowstone River valley. They also lie on the northern edge of the Yellowstone geothermal field. Most hot springs within the Yellowstone field actively deposit siliceous sinter, and have base temperatures in excess of 250^{o} C (Fournier, White and Truesdell, 1975). These hot spring systems are thought to derive their heat from a molten or partially crystallized rhyolitic

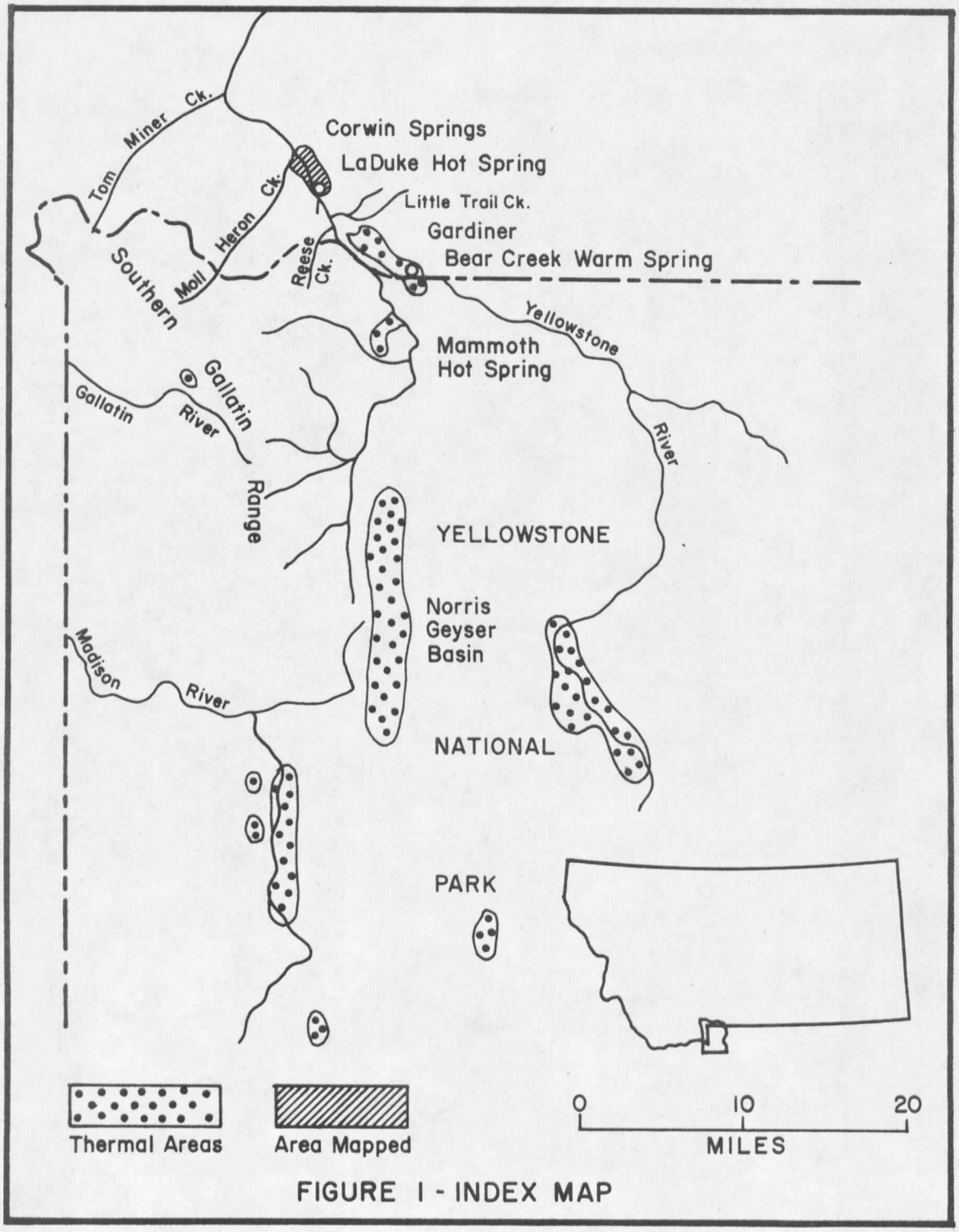


FIGURE 1 - INDEX MAP



PLATE 1. View to the north at the junction of the Yellowstone River and Bear Creek of the travertine deposit at Bear Creek warm spring lying on upturned Paleozoic and Mesozoic sedimentary rocks. Pliocene basalts cover the Gardiner fault zone in the immediate background.



PLATE 2. View west from the travertine deposit at La Duke Hot Spring with upturned Paleozoic and Mesozoic sedimentary rocks at Devils Slide on Cinnabar Mountain in the background.

magma body lying at a depth of five km beneath the Yellowstone volcanic plateau (Eaton et al, 1975).

Regional Setting

The Corwin Springs-Gardiner area occupies a transitional position between the Middle Rocky Mountain and the Northern Rocky Mountain physiographic provinces (Thornbury, 1965). The Beartooth block, an uplifted mass of Precambrian crystalline rock bounded on the southwest by the Gardiner reverse fault, borders the thermal area on the north and east. The southern Gallatin Range, a horst block structure, lies to the west and south of the Corwin Springs-Gardiner system. Andesite and dacitic flows, mudflows, and volcanic breccias of the Eocene Absaroka-Gallatin volcanic field cover extensive areas of both uplifted blocks, and are remnants of a more extensive cover (Chadwick, 1970). The Yellowstone River valley, of probable early Eocene age, was exhumed from beneath the volcanic cover and now separates the two uplifted blocks. The regional terrain is very mountainous, displaying as much as 5,000 feet of relief above the floor of the Yellowstone River valley, which has an altitude of 5,000 feet or more in the Corwin Springs-Gardiner area. Glaciers have moved down the Yellowstone River valley from sources within the Yellowstone National Park area on at least one occasion during the Pleistocene (Montagne, personal communication, 1976). A veneer

of glacial till and outwash alluvium remains on the valley floor and walls.

Objectives and Procedure

This study is an attempt, based on geologic observations only, to determine the circulatory patterns, recharge mechanisms, and heat source of the Corwin Springs-Gardiner geothermal systems. These systems are of particular interest in that although they lie in close proximity to the magmatic heat-driven Yellowstone systems, they bear close genetic resemblance to many of the thermal spring systems throughout western Montana. The quantity of heat and geothermal fluids that the Corwin Springs-Gardiner system might derive from the Yellowstone field is in question here, as is the present intensity and volume of the thermal circulatory system at depth.

The structural and lithologic controls of the Corwin Springs-Gardiner geothermal features were investigated during the summer of 1975 by means of detailed mapping in the La Duke Hot Spring area (Figure 1, page 2), and reconnaissance of the northwest corner of Yellowstone National Park, Cinnabar Mountain, and the Gardiner fault zone with the guidance of published geologic reports. Detailed geologic data were recorded on 1:20,200 scale black and white aerial photos. Examination of regional ERTS photos allowed extension of known fault trends.

Previous Investigations

No work has been published exclusively concerning the controls and origins of the thermal features along the Gardiner fault. However, Waring (1965) lists discharge temperatures for the hot springs, and Balster and Groff (1972) briefly describe possible heat sources for hot springs in the upper Yellowstone River valley. The American Association of Petroleum Geologists (1973) and the Montana Bureau of Mines and Geology (Balster, 1974) have published geothermal gradient maps based on oil and gas well data from the eastern portion of Montana. Unfortunately, coverage does not include the Corwin Springs-Gardiner area. Fraser et al (1969), in their report on the geology of the Gardiner area, briefly describe and map the extent of travertine deposits north of Gardiner, and note the existence of thermal springs at Bear Creek and at La Duke. Numerous papers, however, have been published on the geothermal fields within Yellowstone National Park. Fournier and Truesdell (1970); Fournier, White, and Truesdell (1975); White, Fournier, Muffler, and Truesdell (1975); and Truesdell and Fournier (U.S. Geological Survey, Open-file report) describe the physical and chemical properties of the geothermal systems within the Park. Much of their work is based on data obtained by research drilling in selected thermal areas. Chadwick and Kaczmarek (1975) discuss several models for hot springs in adjacent areas of western Montana.

U. S. Geological Survey studies by Fraser et al (1969) and Ruppel (1972) provide information on the stratigraphic section and structure near Gardiner and the northwest corner of Yellowstone National Park. Papers by Wilson (1934a,b), Spencer (1959), Foose et al (1961), and Brown (1961) also contribute to these subjects. Iddings (1899), Chadwick (1970), Prostka and Smedes (1972), and Shaver (1974) describe the distribution and character of Tertiary eruptive centers and extrusives. Christiansen and Blank (1972) discuss the phases of Quaternary rhyolitic volcanism that produced the thermal features occurring within the Park today. Hamilton (1960) and Love (1961) distinguish tectonic features active in the Quaternary in the Yellowstone Park-Hebgen Lake area. Smith et al (1974) and Eaton et al (1975) present models of the subsurface geology of Yellowstone National Park and vicinity based on gravity, seismic, and aeromagnetic data.

Chapter 2

GEOLOGIC SETTING

Local Stratigraphy

More than 10,000 feet of marine and terrestrial Paleozoic and Mesozoic sedimentary rocks accumulated on the Precambrian crystalline basement before the beginning of Tertiary time. About 3,000 feet of Paleozoic marine sedimentary rocks are exposed in the southern Gallatin Range (Ruppel, 1972). The lithology includes limestone, dolomite, and volumetrically lesser amounts of clastic rock. All systems are represented except the Silurian. Paleozoic rocks crop out at Cinnabar Mountain and at Bear Creek, though faulting removed formations older than Ordovician at Cinnabar Mountain and older than Mississippian at Bear Creek (Figure 2; Plate 1, page 3; and Plate 2, page 4).

More than 8,000 feet of Mesozoic rocks overlie the Paleozoic sequence (Figure 2). Outcrops of Triassic and Jurassic rocks at Cinnabar Mountain display about 1,000 feet of marine sandstones, siltstones, and limestones. More than 5,000 feet of marine and nonmarine clastic rocks were deposited from Late Jurassic to Late Cretaceous time (Fraser et al, 1969). Exposures of these rocks on Cinnabar Mountain include thick sequences of sandstones, shales, and mudstones. A list of the formations and rock descriptions is included in Appendix A, page 72.

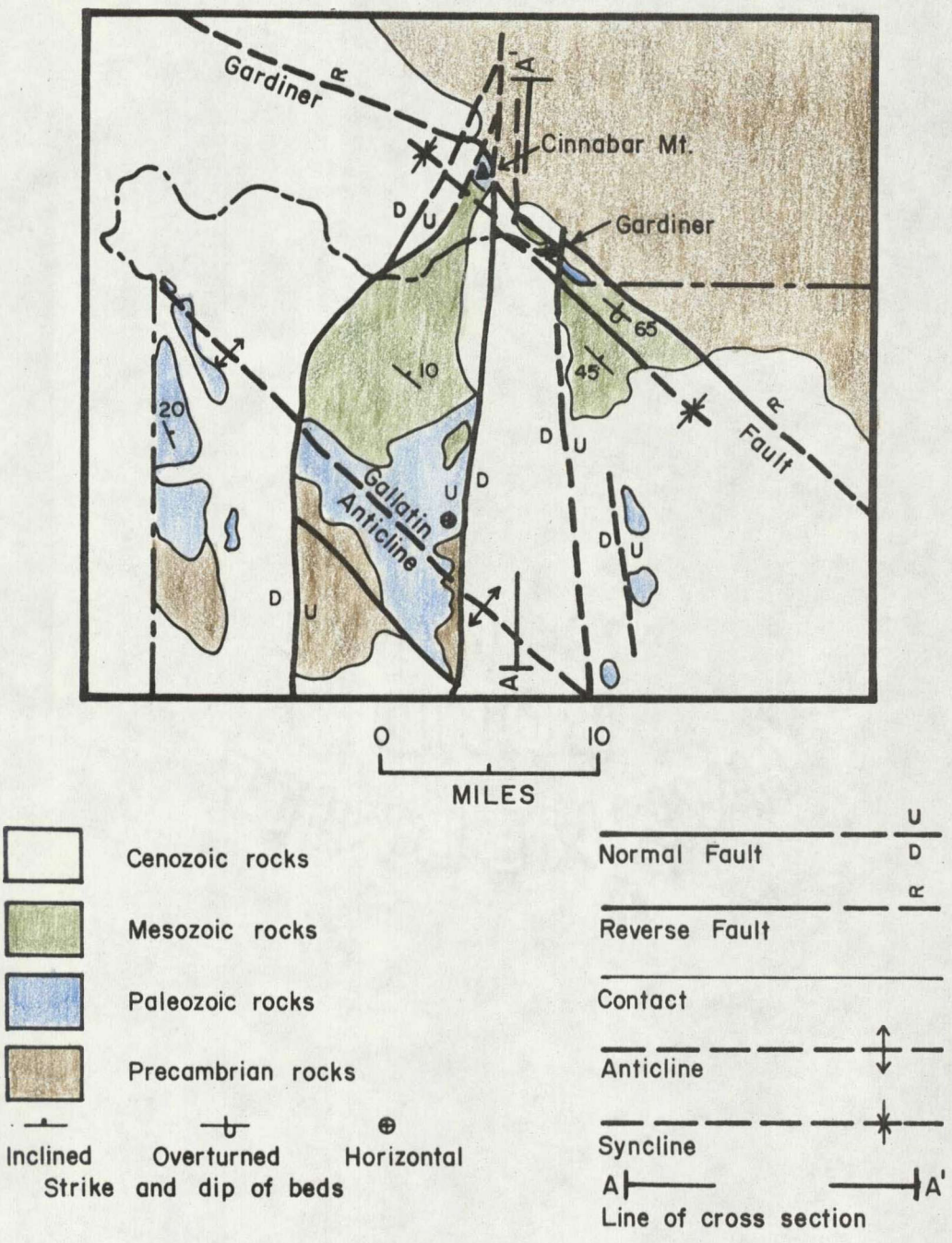


FIGURE 2 GENERALIZED BEDROCK GEOLOGY - GARDINER REGION (modified from Wilson (1934), Frazer (1969) and Ruppel (1972)

Cenozoic Structures and Faults

The Gallatin anticline. The upper reaches of the Yellowstone River drainage have been subjected to intense tectonism and volcanism from the Late Cretaceous to the present. Eastward regression of a Cretaceous seaway, in response to a rising landmass to the west, signaled the beginning of the Laramide period of deformation and uplift. A moderate compressional force from the southwest produced regional folding along northwest-trending axes, followed by differential uplift of crystalline blocks along northwest-trending of high angle reverse faults and thrust faults. Laramide faults may have followed northwest and north-northeast-trending Precambrian faults or structural weaknesses in the crystalline basement (Fraser et al, 1969). Compressional deformation persisted into the early Eocene and raised the sedimentary section in the northwest part of present day Yellowstone National Park into the gentle northwest-trending Gallatin anticline (Ruppel, 1972), (Figure 2). Opposing high-angle reverse faults on the north and south limbs of this anticline depressed the crest of the anticline between them. The northeast-dipping Gardiner reverse fault, passing through Gardiner, Montana, forms the southern boundary of the Beartooth uplift to the north of the anticline, whereas the Grayling Creek fault forms the northern boundary of an uplift of Precambrian crystalline rock to the south of the anticline, in the vicinity of Mount Holmes (Figure 3).

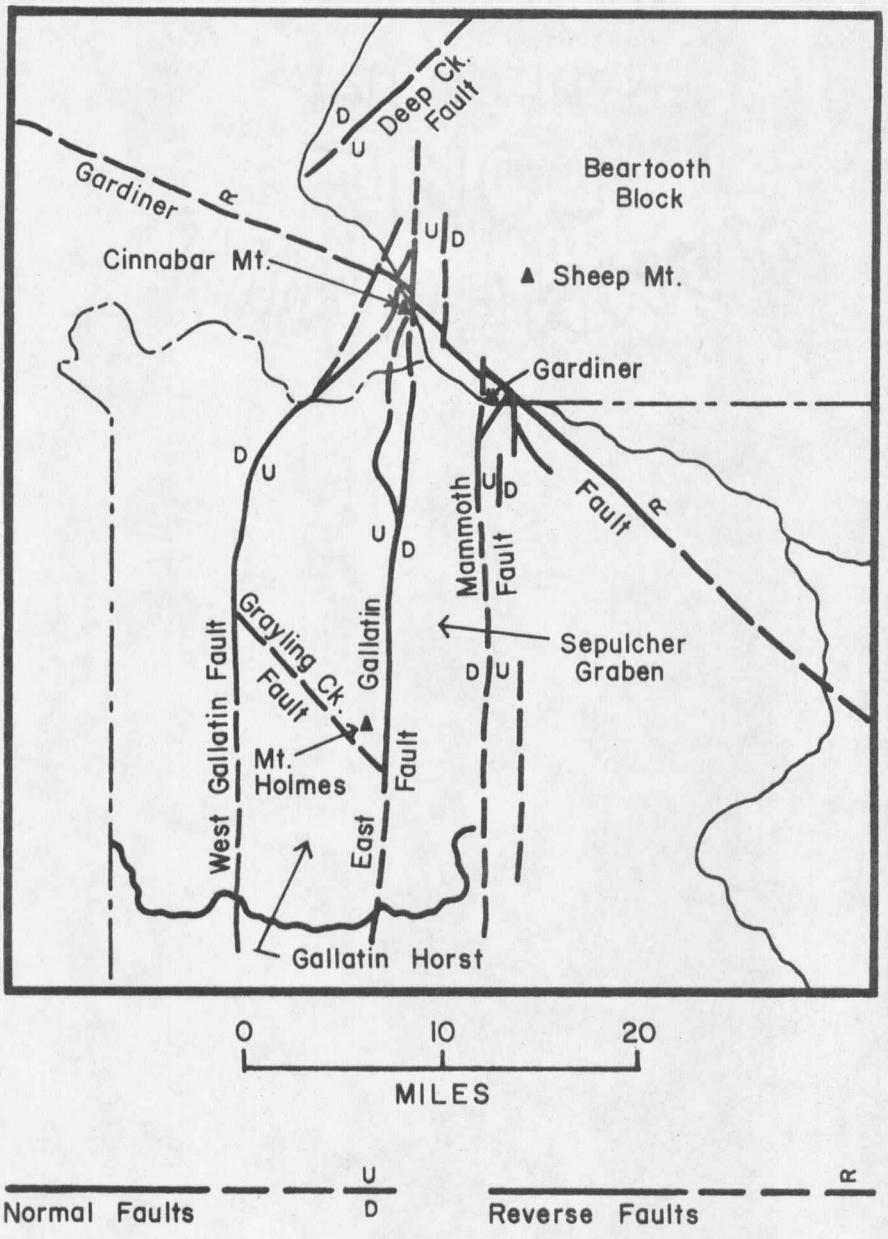


FIGURE 3 MAJOR FAULT ZONES AND STRUCTURAL FEATURES - GARDINER REGION (modified from Frazer (1969), Ruppel(1972)

The Gardiner fault. The Gardiner fault is a steeply northeast-dipping imbricate reverse fault zone, along which is preserved nearly 10,000 feet of Paleozoic and Mesozoic sedimentary rocks in its footwall block. The fault zone ranges from .25 to one mile wide. It emerges from beneath Tertiary volcanic cover southeast of the Grand Loop Road in Yellowstone National Park, and extends northwest along Rescue Creek towards Gardiner, Montana (Plate 3). The fault zone passes along the base of Sheep Mountain just north of Gardiner but is buried beneath basalt flows of probable early Pleistocene age. The fault zone re-emerges at Little Trail Creek, to be progressively offset to the northeast around the northern flanks of Cinnabar Mountain by younger north-trending normal faults (Figure 3, Plate 4, and Plate 5). A northwest trending zone of very coarse autoclastic fragments in Precambrian granitic gneiss marks the location of part of the Gardiner fault zone 0.25 miles uphill and to the northeast of La Duke Hot Spring (Plate 6 and Plate 7). The fault zone juxtaposes crystalline Precambrian rock of the Beartooth uplift against rock units ranging in age from Ordovician to Cretaceous at different localities along its exposure. The sedimentary units are dragged up and are locally overturned along the fault zone as exposed at Cinnabar Mountain and at Mount Everts.

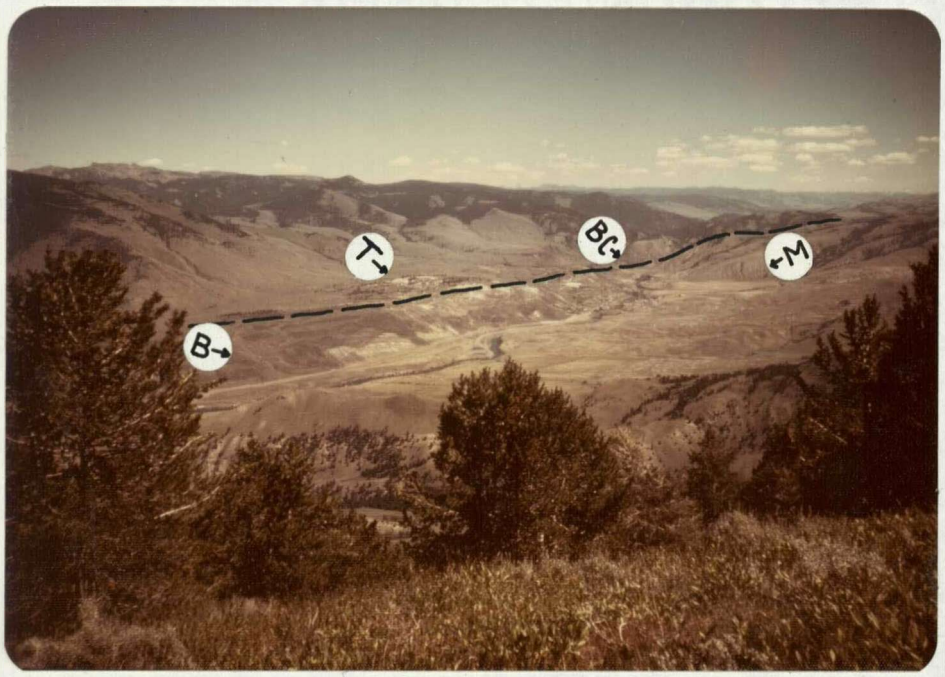


Plate 3. View toward the east from Electric Peak of travertine deposits (T) and Pliocene basalt flows (B) at Gardiner. The Gardiner fault zone passes beneath these deposits starting at the mouth of Bear Creek (BC). A branch of the Mammoth fault (M) defines the base of the northwest flank of Mount Everts and enters the Gardiner fault zone near (BC).

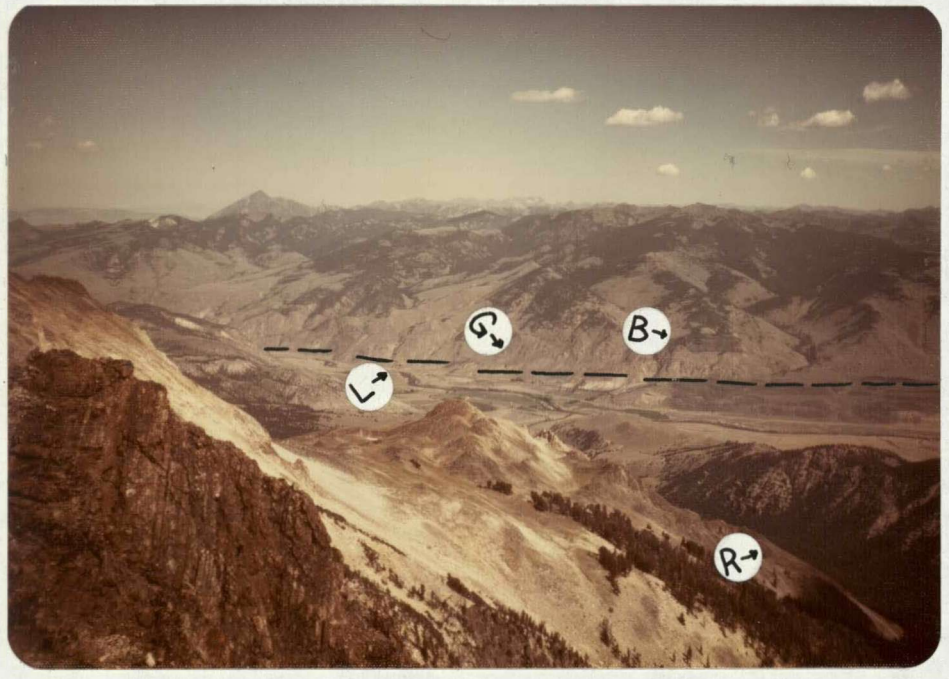


PLATE 4. View toward the north from Electric Peak of the La Duke Hot Spring area. The Reese Creek fault (R) enters the Beartooth block at La Duke Hot Spring (L). The Gardiner fault zone (G) passes through La Duke Hot Spring along the northeastern wall of the Yellowstone River Valley. Offset basalts (B) indicate Quaternary activity on the Gardiner fault zone.



PLATE 5. Trace of the Gardiner fault on the northern flank of Cinnabar Mountain looking to the northwest from a point .5 miles southeast of Corwin Springs. (Te = Eocene intrusive, pK = pre-Cretaceous sedimentary rocks, P€ = Precambrian rock)

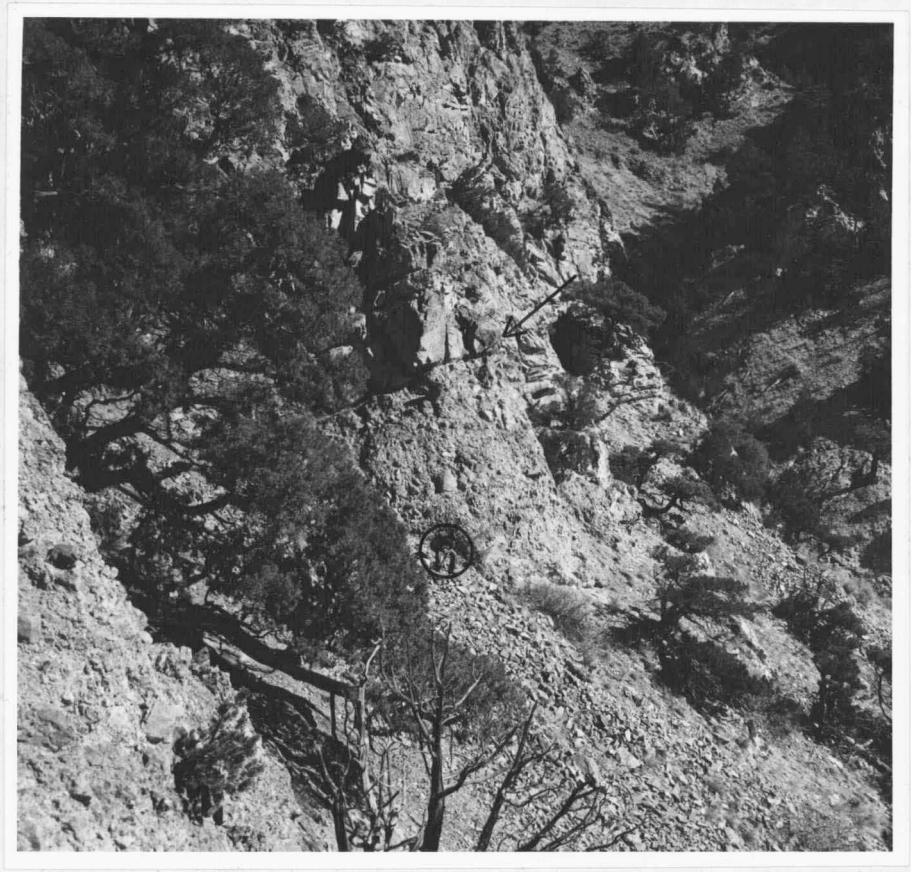


PLATE 6. Fault breccia in granitic gneiss of the Gardiner fault zone .25 miles northeast of La Duke Hot Spring. Contact of undisturbed granitic gneiss with breccia zone indicated by arrow. Zone strikes approximately N50W and dips 50°NE. (note circle around man for scale)



PLATE 7. Gardiner fault zone breccia (bxa) showing boulder sized clasts of granite .25 miles northeast of La Duke Hot Spring. Cinnabar Mountain lies in the background to the northwest.

The Gallatin horst. As uplift of the Beartooth block and the Precambrian block south of the Grayling Creek fault proceeded, a horst block comprising the present southern Gallatin Range rose on a north-northeast trend between the East Gallatin and West Gallatin normal faults (Figure 3, page 12). These faults are traceable from the southern end of the Gallatin Range northward into the Beartooth block, where they cause apparent lateral offsets in the trace of the Gardiner fault on the southeast and northwest sides of Cinnabar Mountain. Maximum displacements of 4,000 to 5,000 feet have been observed on the East Gallatin fault (Iddings, 1904; Wilson, 1934a; Fraser et al, 1969; Ruppel, 1972), whereas approximately 2,500 feet of displacement have been noted on the West Gallatin fault (Ruppel, 1972). Displacement decreases drastically as the faults scissor closed into the Beartooth block. These faults probably formed as the block uplift commenced during Laramide compression and have been intermittently active into the Pleistocene (Love, 1961; Ruppel, 1972).

The Gallatin horst block may be a product of resistance to Laramide compressional deformation which grew on a north-south axis between the Gardiner fault and the Grayling Creek fault. Paleocene sills and laccoliths intruded along the Paleozoic and Mesozoic rocks probably caused the section to behave rigidly in response to compression (Shaver, 1974). Compressional stresses were relieved by creation of the normal faults that now define the Gallatin horst. Precambrian

gneiss in the hanging wall block of the Gardiner fault rests against Ordovician Bighorn Dolomite in the footwall block at the northern end of Cinnabar Mountain. The same Precambrian gneiss rests against Cretaceous Telegraph Creek Sandstone at Little Trail Creek, three miles southeast of Cinnabar Mountain (Figure 2, page 10). Reverse offset apparently progressed further at this location than at Cinnabar Mountain with the result that the Gardiner fault is offset as it approaches Cinnabar Mountain approximately 0.5 miles to the northeast by the Reese Creek extension of the East Gallatin fault (Figure 3, Page 12, and Plate 4, page 15). After passing over the north flank of Cinnabar Mountain, the Gardiner fault is offset 0.25 miles back to the southwest by the Mol Heron Creek extension of the West Gallatin fault. This apparent lateral displacement results from the vertical displacement of the northeastward dipping Gardiner fault zone. Figure 5, page 31, depicts this fracture pattern in greater detail.

The Gallatin horst is similar to the compression resistant block uplifted along the reverse Beartooth fault on the northeast front of the Beartooth block near Red Lodge. This block is bordered by two tear faults having up to 10,000 feet of lateral displacement (Foose et al, 1961). The Reese Creek and Mol Heron Creek faults correspond to the tear faults at Red Lodge but show much less lateral displacement. Shallower dips and greater imbrication along the

reverse Beartooth fault permitted greater lateral displacement of the reverse fault zone at Red Lodge than at Cinnabar Mountain.

The Mammoth fault. The Mammoth fault and related fractures are westerly dipping normal faults with up to 4,000 feet of displacement (Fraser et al, 1969; Ruppel, 1972). They extend from the vicinity of Norris Geyser Basin northward into the Gardiner fault zone between Bear Creek and Gardiner (Plate 3, page 14). The Gardiner fault zone, where exposed, is sheared by the Mammoth fault. The Mammoth fault, like the East and West Gallatin faults, appears to scissor closed rapidly as it enters the Beartooth block. The upturned Paleozoic and Mesozoic units at the juncture of the Mammoth and Gardiner faults are greatly disturbed, preventing accurate measurement of displacement along the Mammoth fault.

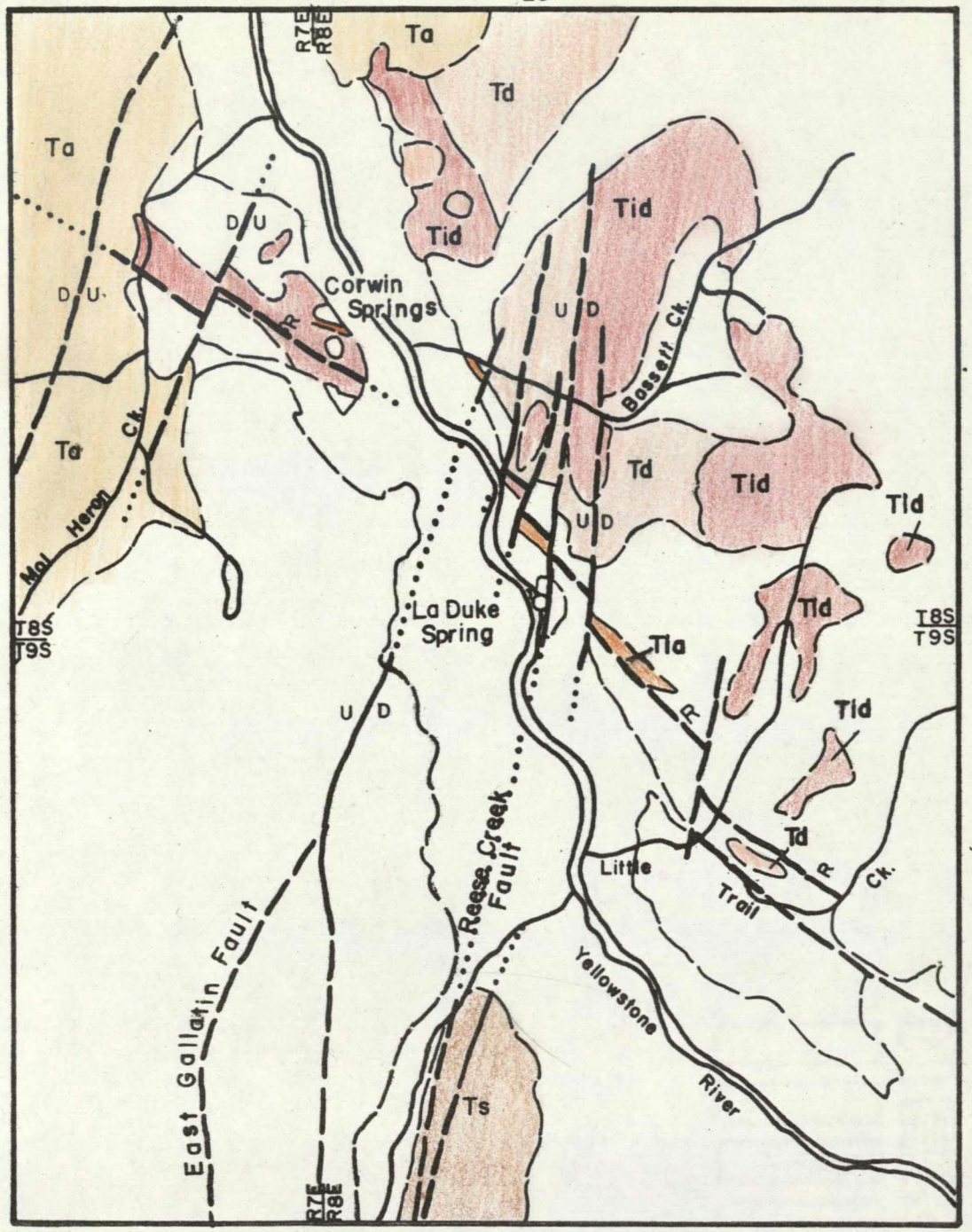
The Sepulcher graben. Downward displacement of the crustal block between the Mammoth and East Gallatin faults has preserved nearly 5,000 feet of Eocene volcanics on top of the pre-Tertiary section. This structure is known as the Sepulcher Mountain graben. The graben effectively truncates the axis of the Gallatin anticline between Roaring Mountain and Mount Holmes and plunges at a gradually steepening angle northward under the Gardiner fault. A segment of the Gallatin anticline is probably preserved in the Sepulcher graben, although the northern limb is most likely oversteepened by the greater displacement

of the graben in its northern extent relative to dip angles observed on the Gallatin horst.

Cenozoic Volcanism

Eocene volcanism. Widespread dacitic and andesitic volcanism accompanied the last stage of displacement along the Gardiner fault zone during Eocene time. All of the Gardiner region was covered by thick sequences of breccias and flows that were part of the Absaroka-Gallatin volcanic field (Chadwick, 1970). Major centers of eruption in the Gardiner area include Electric Peak, Bunsen Peak, and several sources to the northeast on the Beartooth block (Fraser et al, 1969). Electric Peak was the primary source for the volcanics preserved in the Sepulcher graben.

The Gardiner fault zone also served as a minor conduit for Eocene lavas. Numerous dacitic and andesitic dikes occupy positions within the fault zone and parallel to the fault plane (Figure 4). These dikes are well exposed near La Duke Hot Spring and on the north flank of Cinnabar Mountain where they provide the most reliable means of identifying the trace of the Gardiner fault. The dikes generally penetrate Precambrian granitic gneiss and fault breccias of the hanging wall block. However, a few dikes on Cinnabar Mountain intrude limestone of the footwall block close to the fault trace. These dikes are truncated and offset along the Gardiner fault zone by the Reese



Ta — Andesite Breccia Extrusive

Tia — Andesite Intrusive

Td — Dacite Extrusive

Tid — Dacite Intrusive

Ts — Sepulcher Formation (Rhyodacite ash flow - correlation uncertain)

Reverse Fault

Normal Fault

Contact

0 — 1 MILES

FIGURE 4. DISTRIBUTION OF EOCENE INTRUSIVES AND EXTRUSIVES NEAR CORWIN SPRINGS, MONTANA (modified from Wilson, 1934a, Fraser, 1969, and U.S. Geological Survey Map I-711, 1972)

Creek and Mol Heron normal faults. Several small intrusions of dacite and dacite breccia cut the hanging wall block within one mile of the fault zone between Little Trail Creek and Corwin Springs. The Gardiner fault zone probably controlled the ascent of these magmas as well. Most displacement along the Gardiner fault zone appears to have been accomplished before the Eocene intrusives were emplaced, as indicated by the lack of major reverse displacement within those intrusives. However, the Gardiner fault may be responsible for some minor brecciation and gouge within the dikes on Cinnabar Mountain, indicating some activity along the fault zone at the time of intrusion. These rocks are described in greater detail in Appendix B, page 75.

Quaternary volcanism. Following this early volcanic episode, volcanism subsided in the Gardiner area until Pliocene or Pleistocene time when a series of basalts flowed down the Yellowstone River valley from probable sources within Yellowstone Park. At least five flows make up the basalt bench extending north of Gardiner from Deckard Flats near Bear Creek to Little Trail Creek. Another remnant outcrop lies on an old erosional surface above La Duke Hot Spring. The age and source of this sequence of basalts is uncertain since erosion has destroyed any links with possible sources upstream. Source conduits within the Gardiner fault zone north of Gardiner were suggested by Wilson (1934a) but evidence is not conclusive.

The basalts resemble those of the Junction Butte Basalt Group in their black, aphanitic appearance and position on top of a late Tertiary erosional surface cut into unconsolidated sediments and pre-Eocene rocks. The absence of ash flow tuff clasts of the Yellowstone Group in the unconsolidated sediments beneath the basalts suggests that the Gardiner basalts were erupted, as were the Junction Butte Basalts, prior to the initial outbreak of rhyolitic lavas on the Yellowstone Plateau (Fraser et al, 1969). Christiansen and Blank (1972) have identified vents of the Junction Butte Basalt Group at the east end of Mount Everts. Flows from these vents could have had access to the Gardiner area by means of either the Yellowstone River or the Gardiner River drainage. Several Pliocene basalt flows have been dated by Bush (1967) at Hepburn's Mesa 15 miles down the Yellowstone River from Gardiner. No correlation between the Gardiner and Hepburn's Mesa basalts has been established.

Three cycles of rhyolitic tuff eruption and caldera collapse began on the Yellowstone Plateau in the Early Pleistocene. Periodic extrusion of rhyolite flows, domes, and basalt flows accompanied the voluminous tuff eruptions. The oldest flows have been dated at less than 2.4 million years old (Christiansen and Blank, 1972). The youngest flows were extruded as recently as 70,000 years ago (Christiansen and Blank, 1972). The Sepulcher graben was the site of extrusion of several young flows and domes. These extrusive

centers were peripheral to the main caldera. No volcanics were erupted in the Corwin Springs-Gardiner area during this period, although the Yellowstone River valley was deeply buried under rhyolite tuff at least once as evidenced by remnants of rhyolite ash flows on Mount Everts, in the Bear Creek drainage north of Gardiner, and in Tom Miner basin northwest of Corwin Springs. Caldera collapse occurred on three occasions centered around the Yellowstone Lake area as rapid removal of magma during the tuff eruptions left the roof of the magma chamber unsupported.

Regional Seismicity

The geologic record of the Gardiner area suggests that the area has been seismically active since the late Cretaceous. The mechanical nature of this activity has changed with time. Laramide compressional stress subsided by Middle Eocene time as indicated by the lack of significant reverse displacement in the Eocene volcanics. A tensional stress regime replaced Laramide compression causing extensive normal faulting in the upper Yellowstone region. Tensional stresses became most intense during the Pliocene and have continued into the Holocene (Ruppel, 1972). After initially developing during the Laramide, a group of north-south trending normal faults acquired most of their displacement during this latest deformational phase. These include the East and West Gallatin faults and the Mammoth fault.

Normal displacement also occurred during the Holocene along the Gardiner and Grayling Creek faults (Fraser et al, 1969). Such displacement may be observed along the Gardiner fault at Little Trail Creek and southeast of Mount Everts.

The Gardiner area lies within the Intermountain Seismic Belt, a major zone of Holocene seismicity extending from southern Utah to northwest Montana (Smith et al, 1974). The Yellowstone caldera comprises the eastern end of a secondary seismic zone that extends westward through the Hebgen Lake area into central Idaho. Fault plane solutions by Smith and Sbar (1974) and Trimbel and Smith (1973) suggest that north-south extension presently prevails along this secondary seismic zone whereas east-west extension prevails along the rest of the Intermountain Seismic Belt to the north and south. Holocene scarps along the normal Deep Creek fault to the north of Gardiner in the Paradise Valley and along the Teton fault in Jackson Hole to the south provide clear evidence for modern seismic activity. Resurgent magmatic activity beneath the Yellowstone caldera superimposes radial compressive forces upon the more general tensional regime in the vicinity of the caldera (Smith et al, 1974). Crustal shortening in a radial direction is indicated.

Chapter 3

CONTROLS ON THERMAL WATER CIRCULATION

Control on the flow of thermal water in the Corwin Springs-Gardiner thermal systems is exerted by joints, faults, and permeable rock units. A geologic model describing recharge, circulation, and discharge of these thermal systems, and the relative importance of these controlling structures will be developed here. This model is an attempt to explain the geologic setting and physical characteristics of the hot springs. A brief description of the geology of La Duke Hot Spring and Bear Creek thermal springs and the Gardiner travertine deposits will help place the circulation model within the context of the regional geologic picture developed in Chapter 1.

Local Geologic Setting

The Corwin Springs-Gardiner thermal features are aligned within the northwest-trending Gardiner reverse fault zone. La Duke Hot Springs lies at the intersection of the Gardiner fault and the Reese Creek fault as indicated in Figure 5, page 31. Hot water flows from two major sources and from two small seeps in recent colluvium and fractured, silicified limestone bedrock. One major source is actively depositing travertine on the banks of the Yellowstone River and flows at an estimated 100 gpm from a cement-encased reservoir covered by U. S. Highway 89 (Taylor, 1975). The other source is a nonflowing

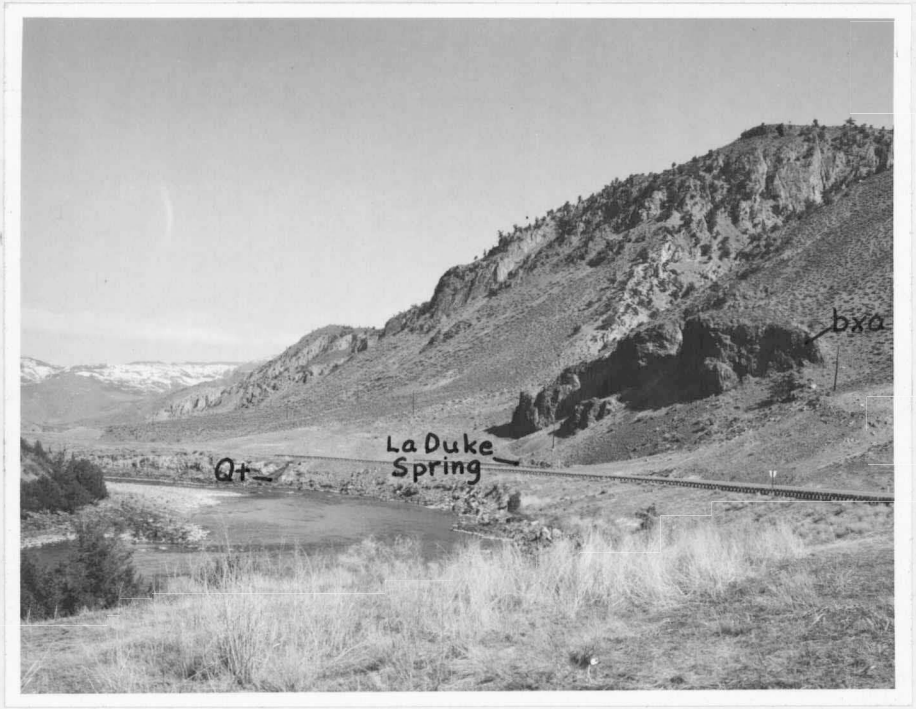


PLATE 8. View to the north of La Duke Hot Spring and cliffy silicified limestone breccia outcrop. (Qt = Quaternary travertine, bxa = fault breccia)

cement-encased pool lying to the east of the highway. The two seeps drain into the borrow pit about 30 yards to the south on the east side of the highway. La Duke Hot Spring was the source of hot water for the resort community at Corwin Springs in the late 1800's.

These springs lie at the base of a prominent cliff composed of a coarse angular fault breccia (Figure 5). Most of the breccia is a highly silicified, dark gray, sugary textured rock. However, textures visible in the rock on the upper part of the outcrop suggest that dacite makes up a portion of this breccia. These dacite fragments may come from a dacite dike which cuts the granitic gneiss of the Beartooth block immediately uphill from the breccia outcrop. The lower part of the breccia outcrop is an altered limestone which may be part of the Madison Group as suggested by its light gray color and microscopically visible ghosts of crinoid stem cross sections (Plate 9) (D. L. Smith, personal communication, 1976). This interpretation is uncertain but is supported by the location of this outcrop approximately on the strike projection of the upturned Madison Group at Cinnabar Mountain across the Yellowstone River valley to the northwest. The structural orientation of the limestone outcrop at La Duke Hot Spring is not measurable due to poor exposure. The limestone outcrop may represent the eastern margin of the Gallatin horst. However, the margin at this point must be significantly downdropped, relative to the horst at Cinnabar Mountain, by normal displacement along the

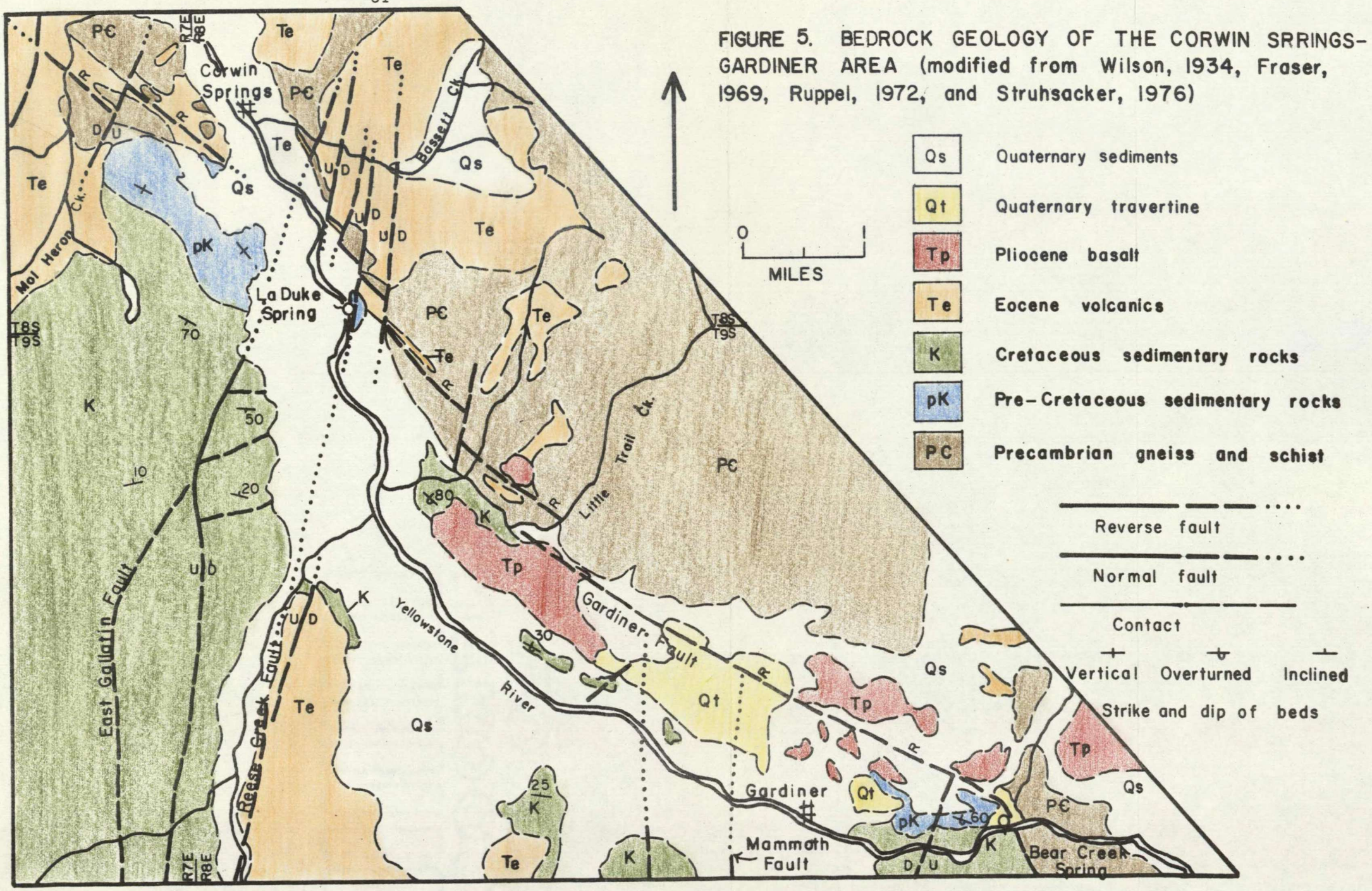
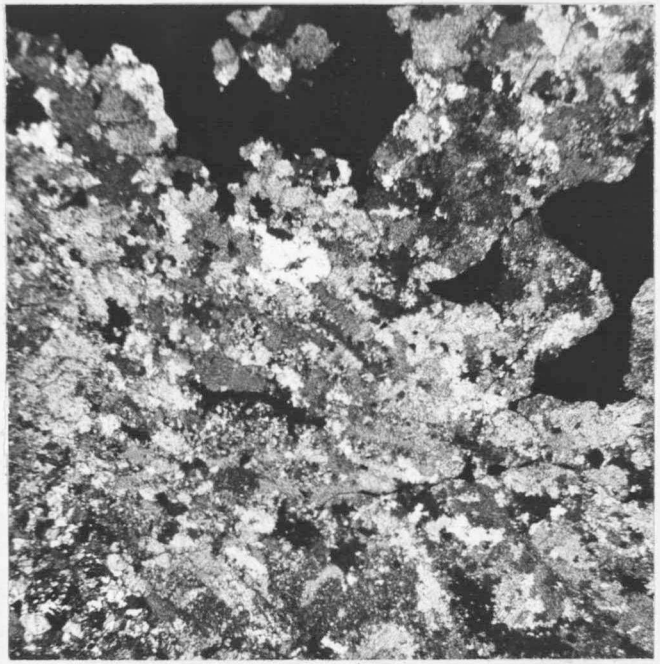


FIGURE 5. BEDROCK GEOLOGY OF THE CORWIN SRRINGS-GARDINER AREA (modified from Wilson, 1934, Fraser, 1969, Ruppel, 1972, and Struhsacker, 1976)



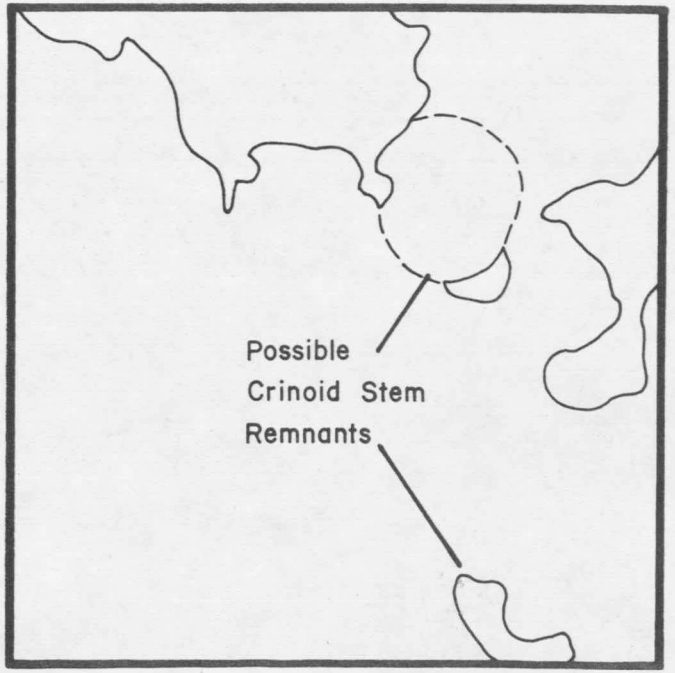


PLATE 9 PARTLY SILICIFIED LIMESTONE SHOWING POSSIBLE CRINOID STEM REMNANTS FROM LA DUKE HOTSPRINGS. (CROSSED NICOLS)

numerous elements of the Reese Creek-East Gallatin fault. These elements penetrate the Gardiner fault zone between Little Trail Creek and Cinnabar Mountain. The vertical orientation of the sedimentary units dragged up in the footwall block of the Gardiner fault zone frustrates any attempts to determine the amount of vertical displacement that has occurred along the Reese Creek fault zone in the vicinity of La Duke Hot Spring. The Reese Creek fault and associated fractures appear to continue northward into the Beartooth block as much as one mile beyond the Gardiner fault zone as indicated by bedrock fracturing and topographic linears visible on the ground and on aerial photos (Figure 3, page 12). The fractures scissor shut as they cut into the Beartooth block.

The Bear Creek thermal spring lies near the intersection of the Gardiner fault and a branch of the Mammoth fault (Fraser et al, 1969) (Figure 5). The spring presently flows at less than one gpm but has deposited a .3 square mile travertine mound during the Pleistocene and Holocene. The travertine rests on top of an upturned sequence of Paleozoic and Mesozoic sedimentary rocks. Reverse faulting has placed Precambrian schist against the Madison Limestone. Normal faulting along the Mammoth fault zone has severely sheared the sedimentary rocks in the vicinity of Bear Creek spring. North-northeast trending elements of the Mammoth fault zone appear to terminate within the Gardiner fault zone though Quaternary cover may obscure

continuations of these fractures to the north (Fraser et al, 1969). Bear Creek spring issues from the upthrown footwall block of the Mammoth fault which includes the uplifted area of Mount Everts to the east of the Mammoth fault.

The Gardiner travertine deposits discontinuously cap the Pliocene-Pleistocene basalt bench immediately north of Gardiner (Figure 5). The basalt bench, composed of five flows, covers upturned Mesozoic sediments preserved as the footwall block of the Gardiner fault zone within the Sepulcher graben. The travertine deposits locally attain thicknesses of greater than 60 feet. The greatest thicknesses, as determined by reconnaissance field checks, occur in the vicinity of possible intersections of elements of the Mammoth fault zone with the Gardiner fault as mapped by Ruppel (1972). One such intersection may occur near the travertine quarries slightly northwest of Gardiner, the site of the thickest travertine accumulation. The travertine also covers and is cut by numerous slump fractures that break the basalt bench parallel to the trend of the Gardiner fault zone. These fractures are products of a reactivation at depth of the Gardiner reverse fault zone in a normal sense during Pleistocene and Holocene time (Fraser et al, 1969). The majority of the fractures are probably products of slumping of the basalts on top of upturned incompetent Cretaceous sedimentary rocks in response to the renewed tectonic activity. They most likely do not penetrate more deeply than the base of the basalt

flows. However, Fraser et al (1969) indicates that several fractures may extend continuously into the Gardiner fault zone below the basalt.

Discharge Patterns

La Duke and Bear Creek thermal springs both discharge from fractures at the intersections of the Gardiner fault zone with the Reese Creek and Mammoth faults respectively. Recent seismic activity in the area maintains these highly fractured zones as open conduits. The Gardiner travertine deposits are products of similarly located Pleistocene springs. The hot water probably rises from a heat source at considerable depth in the Gardiner fault zone. Both La Duke and Bear Creek springs appear to have point sources as indicated by the close spacing of the springs and, in particular, the cone shape of the Bear Creek travertine deposit.

The Gardiner travertine deposits display symmetrically round mounds and several northwest trending linear deposits that suggest control of discharge by the young slump fractures cutting the basalt bench within the Gardiner fault zone. One or two of these linear deposits resemble the elephant back ridges developing presently at Mammoth Hot Springs where thermal water flows outward from a fracture to both sides along its entire length. The elephant back ridges at Gardiner are about .25 miles in length and 20 feet high. The locations of many of the springs and their relative stratigraphic positions are

obscured by the slump fractures described previously and by glacial scouring.

Fault Control of Recharge

Fault zones may aid the recharge process where they provide permeable fractures that continue to great depth. Where seismic activity has sustained open fractures, groundwater may penetrate the otherwise impermeable sedimentary rocks in the Sepulcher graben. Fraser et al (1969) and Ruppel (1972) have suggested that the Gardiner, Mammoth, and East Gallatin-Reese Creek faults have been recently active, as evidenced by the displacement of Pleistocene deposits along those faults. Many fractures related to these fault zones cross the Yellowstone River valley presenting abundant opportunities for water from that drainage to percolate into the bedrock. However, fine-grained river alluvium and glacial till may impede access of water to these fractures. The permeability of the fractures may be low since weathering products and hydrothermal minerals, deposited by circulating hydrothermal fluids, tend to seal fractures rapidly in the absence of repeated movement along the fractures.

Joint Control of Recharge

Abundant bedrock joints with varying orientations provide an important means of recharge for the Corwin Springs-Gardiner thermal circulatory systems (Figure 6). The fractured Precambrian granitic

gneiss and schists of the Beartooth block probably contain greater fracture permeability than most of the Eocene volcanics and Phanerozoic sedimentary rocks in the area. The superposition of Laramide fracturing on Precambrian fracture patterns in the gneiss and schist is a possible explanation for their greater fracture permeability.

Prominent joint trends of likely Precambrian origin, as measured by Spencer (1959) on the eastern part of the Beartooth block, and by Ruppel (1972) in the Gallatin Range and on the southwest part of the Beartooth block, are: N.15°W., N.45°W., N.45°E., and N.65°W. Other joints trend N.55-60°E., N.15°-20°E., N.-S. to N.5°E., and N.85°E., to E.-W. Most fractures are almost vertical except near the overthrust margins of the Beartooth block where shallowly dipping joints have developed in response to intense Laramide compressional stresses (Spencer, 1959). Joint orientations noted by the author between La Duke Hot Spring and Cinnabar Basin in the hanging wall block of the Gardiner fault suggest that Laramide compression and subsequent tensional stress strengthened the N.60°W. and the N.5°-30°E. trends in the vicinity of the intersections of the Gardiner fault zone with the transverse normal faults (Figure 6).

The Precambrian rocks appear to contain relatively fewer mineralized fractures or fractures rendered impermeable by the deposition of clayey weathering products than do the Phanerozoic rocks.

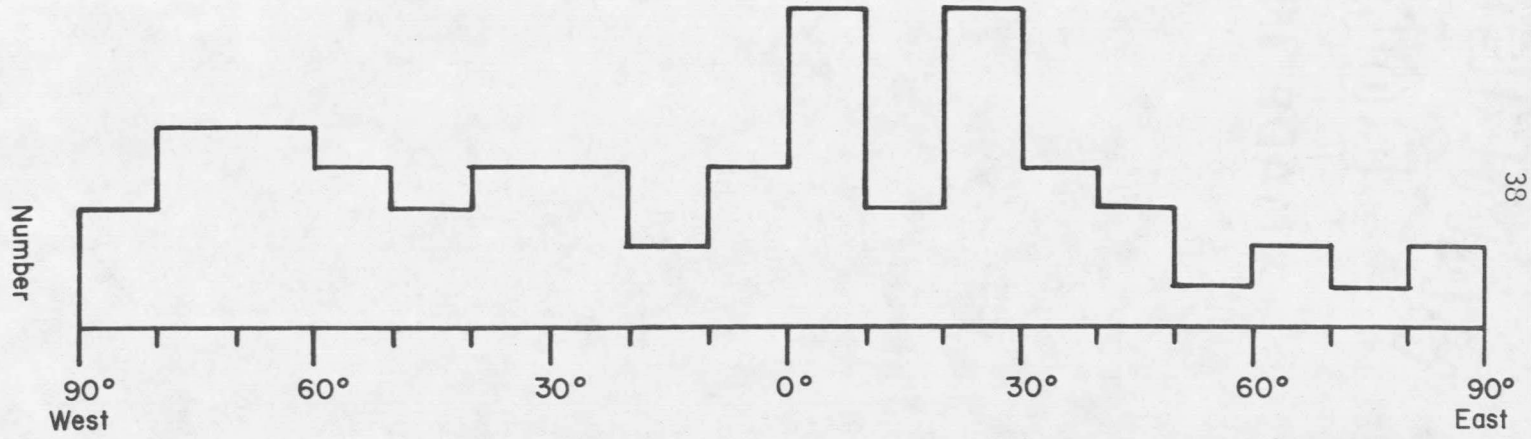


FIGURE 6 HISTOGRAM OF JOINT ORIENTATIONS IN PRECAMBRIAN GRANITIC GNEISS ALONG THE GARDINER FAULT ZONE NEAR LA DUKE HOTSPRING
(Based on 67 measurements)

The incompetent, shaley nature and the great thickness of the clay-rich Mesozoic rocks has inhibited the development and preservation of permeable fractures. The easily weathered Eocene volcanic breccias may suffer similar limitations to the development of fracture permeability. Clays and iron oxides that develop during weathering of the volcanics may effectively clog fractures. The abundance of unmineralized fractures in the granitic gneiss is evidence that this rock may potentially be an aquifer.

The probable high permeability of the fractured Precambrian crystalline rocks suggests that groundwater may percolate to considerable depths through joints in the hanging wall block of the Gardiner fault. The great areal exposure of Precambrian rock on the flanks of Sheep Mountain between Bear Creek and Cinnabar Mountain and the considerable relief of the local drainages could encourage significant recharge of the thermal systems. The lower fracture permeability of Mesozoic rocks preserved in the Sepulcher graben to the south of the Gardiner fault would impede percolation of groundwater to any great depth. Descending cold groundwater in the hanging wall block of the Gardiner fault zone must enter the fault zone at some point during its downward flow (Figure 8, page 46). If the flow of hot water rising in the Gardiner fault zone is sufficiently strong, the density difference between the cold and hot water may force the heavier cold water to greater depths without appreciable mixing of the waters as

shown for the Steamboat Springs, Nevada area (White, 1968). The cold water probably remains within the joints of the hanging wall block during its descent. As the descending water warms sufficiently, it will enter the permeable fractures of the fault zone.

Pressure from thermal expansion of the rising hot water may contribute a major driving force to the hydraulic head propelling the circulating system. For example, in the case of Steamboat Springs, Nevada, White (1968) suggests that thermal expansion of water at 170^{o} C contributes a force equivalent to a head of 900 feet of cold water in a system that circulates to a depth of 10,000 feet. Though temperatures of waters in the Corwin Springs-Gardiner thermal systems noted in the introduction are most likely not as high as those at Steamboat Springs, thermal expansion should contribute to the driving force of the system. If upward flow of water is weak, as is suggested by the present flow rates at the surface, dilution of the rising hot water in the fault zone by the cold water from the hanging wall block is likely. Silica geothermometer values are probably lower than actual reservoir temperatures as a result of this dilution. The expansive travertine terraces at Gardiner indicate that flow of water in the thermal system was more voluminous during the Pleistocene. The decreased flow volume may stem from the filling of fractures in the Gardiner fault zone with calcite from the calcium-rich thermal waters.

Recharge may also have decreased as the climate became drier in the Holocene.

Lithologic Control of Recharge

Porous rock units may significantly control recharge of the Corwin Springs-Gardiner thermal system. Precambrian crystalline rocks, volcanics, and sedimentary rocks may all possess minor intergranular porosity that will permit slow percolation of groundwater. However, a sedimentary unit displaying vuggy or cavernous porosity, in addition to intergranular porosity, may best transport the volumes of water necessary to supply the hot springs that produced the Pleistocene to Recent Gardiner travertine deposits. The voluminous travertine deposits north of Gardiner and the present high calcium content of spring effluent at La Duke and Bear Creek springs suggest that the water spent considerable time in contact with limestone during circulation at depth (Chadwick, personal communication, 1975). The Madison Limestone is the most likely of the Paleozoic and Mesozoic units to satisfy the requirements of a limey, cavernous aquifer for the recharge of thermal waters.

The Madison Limestone consists generally of light gray, massive limestone and dolomitic limestone. The Mission Canyon Limestone of the Madison Group, as depicted in Figure 7 and Plate 10, displays abundant ancient and recent cavities and sinkholes in its upper 300

feet, wherever it is exposed in southern Montana and northwestern Wyoming (Andrichuk, 1955). Reticulate networks of joints enlarged by the same solution processes are also common (Sando, 1974). The solution cavities are thought to be relicts of a widespread karst topography that developed during subaerial exposure of the Mission Canyon Limestone during Late Mississippian to Early Pennsylvanian time (Roberts, 1966). Red calcareous siltstones and sandstones of the Pennsylvanian Amsden Formation fill most of the solution cavities. The Mission Canyon also contains two layers of carbonate breccia which are probable products of collapse after solution of evaporite beds (Roberts, 1966). Laramide uplift exposed the limestones and evaporites to renewed solution processes. Such solution activity is probably active at present.

The Mission Canyon dips northward from the crest of the Gallatin anticline obtaining the proper structural orientation to guide cold groundwater to great depths within the Gallatin fault zone (Figure 8). The exposure of the Landslide Creek Formation at Gardiner requires a minimum depth of 10,000 feet for the Mission Canyon aquifer in that area since this exposed Late Cretaceous unit is separated from the Mission Canyon by 10,000 feet of section. Over-steepening of the northern limb of the Gallatin anticline or superposition of imbricate thrust blocks in the Gardiner fault zone could place the Mission Canyon at a yet greater depth. Normal faulting

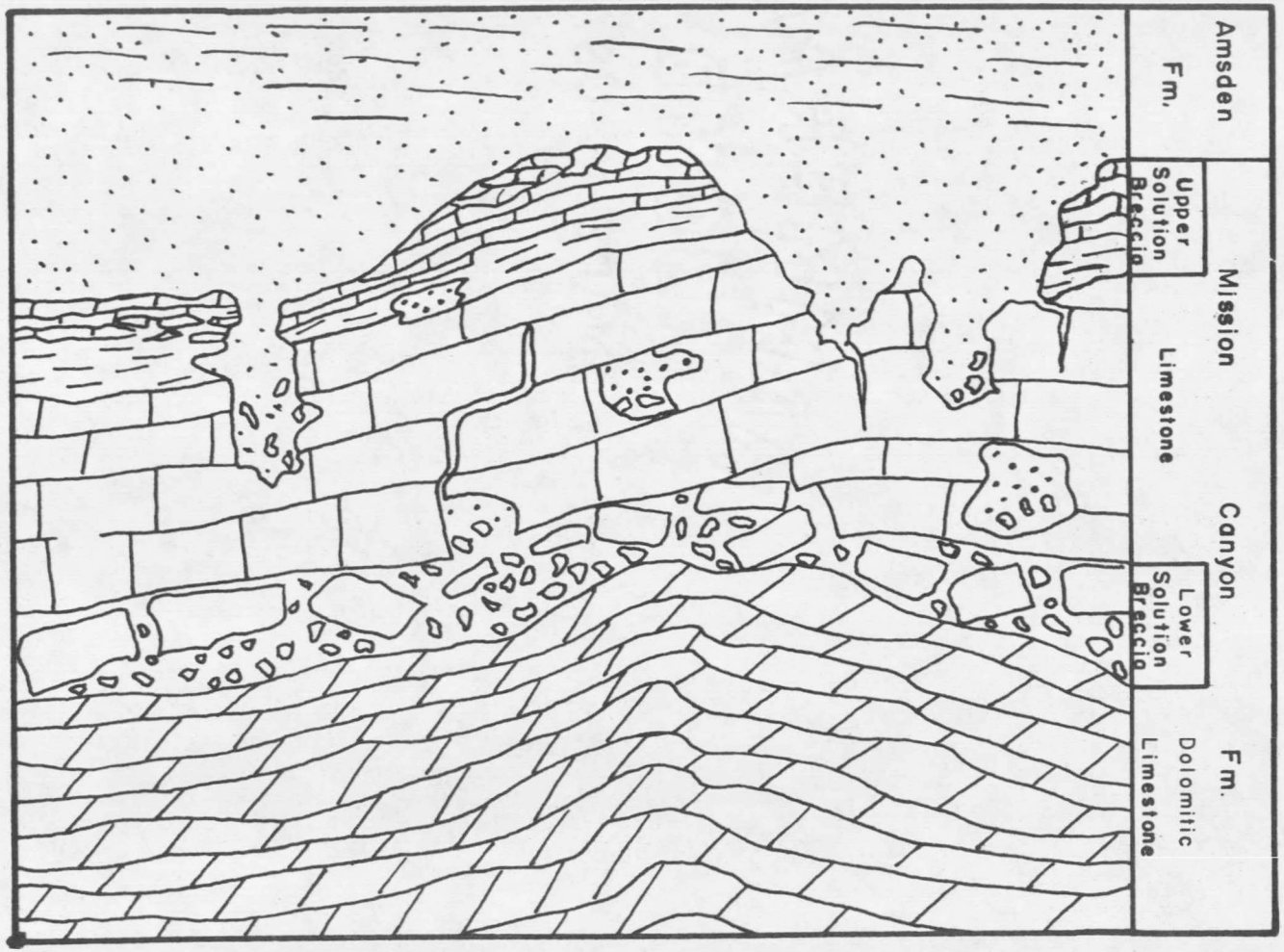


FIGURE 7. SKETCH OF SOLUTION FEATURES IN THE MISSION CANYON FORMATION(modified from Ruppel, 1972, and Sando, 1974)



PLATE 10. A portion of the Mission Canyon Limestone exposed near Devils Slide on Cinnabar Mountain showing cavernous nature of the formation.

along the East Gallatin and Mammoth fault zones dropped the crest of the Gallatin anticline at least 2,000 feet within the Sepulcher graben (Ruppel, 1972). Exposures of the Madison Limestone near the crest of the anticline on the highlands to the east and west of the graben suggest that the limestone may have been exposed at a Tertiary erosion surface that is now covered by nearly 1,000 feet of Quaternary volcanics and sediments of the Yellowstone Group (Figure 2, page 10).

Water from the sluggish drainage system of the Gardiner River probably finds access to the Madison by means of fractures and interflow contacts within the volcanics. The water then follows the permeable zones in the limestone to depths near 10,000 feet within the Gardiner fault zone. Here the water is heated at this depth by processes to be discussed in the next chapter. The limestone has been dragged up and fractured by reverse faulting providing access for the heated water to the Gardiner fault zone. The fault zone acts as the conduit feeding hot springs at the surface.

In accordance with the circulation model described here, the travertine deposits of the Gardiner-Corwin Springs thermal systems are probably products of the solution of limestone by the cold, CO_2-rich groundwater during its descent from the surface. Increasing lithostatic and hydrostatic pressures could sustain the high CO_2 partial pressure and calcium concentration of the descending water even as it is heated at depth. These pressures are released and

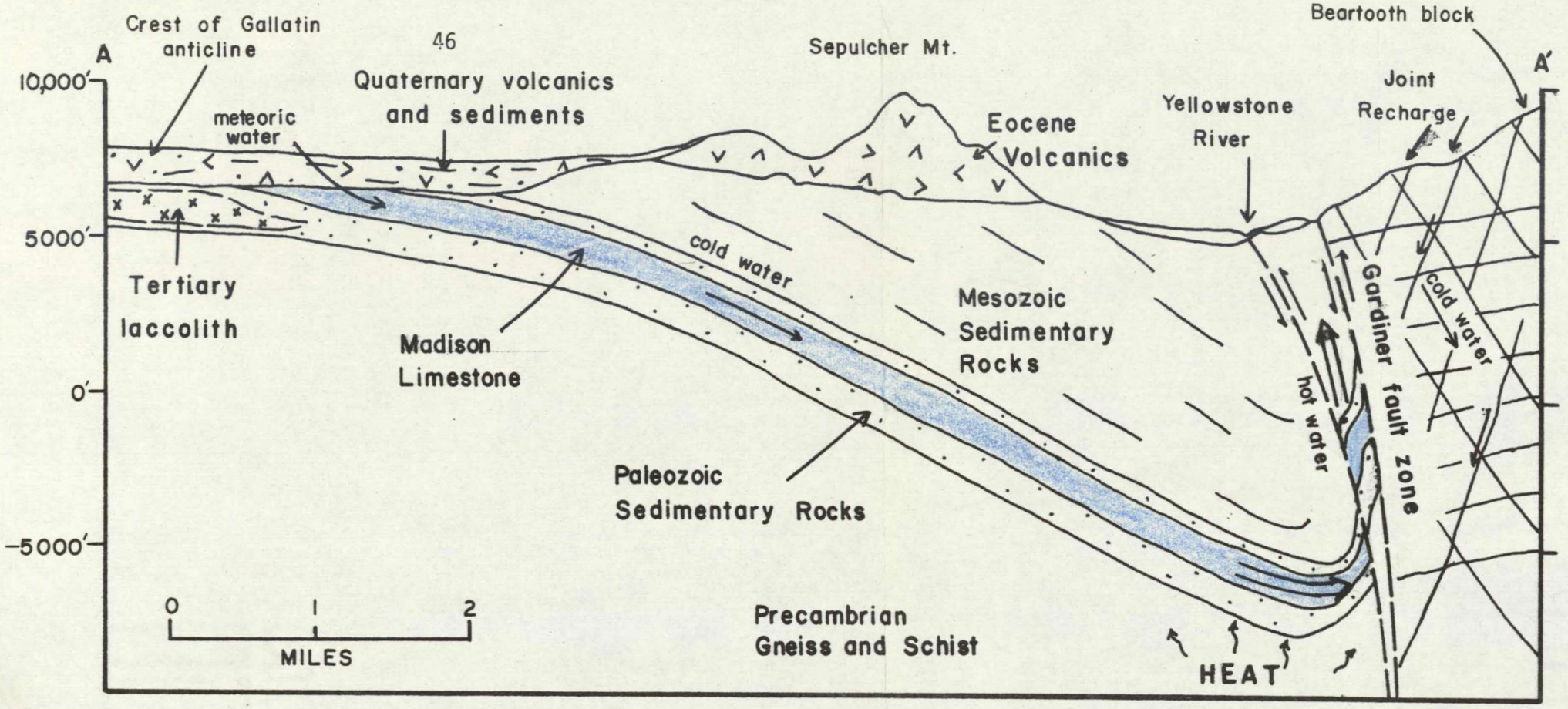


FIGURE 8. GEOLOGIC CROSS SECTION ALONG SEPULCHER GRABEN SHOWING POSSIBLE RECHARGE PATTERN FOR CORWIN SPRINGS GARDINER THERMAL AREAS (refer to Figure 2 for location of line A—A')

CO_2 is driven off as the ascending water approaches the surface. Deposition of travertine results. Heavy travertine deposition may choke the conduits leading to the surface and account for the reduced surface activity of the thermal system at present. The thick travertine deposits directly north of Gardiner lie on the trends of two possible branches of the Mammoth fault zone, which may have served to localize flow at this locality in the Gardiner fault zone. The present absence of springs in this area suggests that fracture conduits feeding the former springs are now tectonically inactive and are sealed. However, continued tectonic activity along the Reese Creek fault and the easternmost branch of the Mammoth fault may sustain the permeability of those fault zones and the flow of hot water at La Duke and Bear Creek springs. Future seismic events could open presently sealed fractures and increase discharge rates.

The recharge mechanisms discussed in this section probably work simultaneously to sustain this thermal system. However, recharge through the Mission Canyon aquifer may be essential to produce the calcium-rich spring effluent and high discharge necessary to have formed the extensive travertine deposits at the surface.

The Mammoth Hot Springs, in contrast to the Corwin Springs-Gardiner thermal system, may obtain most of their hot water from a northward flow within the Mammoth fault zone of water from the Norris Geyser Basin (Truesdell and Fournier, Open-file report). A swarm

of Pleistocene normal faults at Mammoth Hot Springs cause downward displacement to the east and allows most of this hot water to escape into the Gardiner River drainage (Figure 1, page 2, and Figure 3, page 12).

Chapter 4

SOURCES OF HEAT

A model for the source of the heat driving the thermal system in the Corwin Springs-Gardiner area may be built from an understanding of the structural relationships controlling recharge and circulation of water in the system. Geophysical data, collected from studies in Yellowstone National Park and neighboring areas, further define the model. Surface temperatures and spring chemistry provide evidence for the intensity of the heat source. The geologic setting of the Corwin Springs-Gardiner thermal system offers two potential sources of heat. Possible deep circulation of groundwater could expose the water to bedrock warmed by the local normal geothermal gradient. Alternatively, the proximity of this thermal system to the rhyolitic magma body, thought to lie at shallow depth beneath the Yellowstone caldera, may subject groundwater to the higher heat flow associated with the magma body. Geophysical data suggest that a satellite body of magma may lie beneath Gardiner providing an intense source of local heat (Eaton et al, 1975). The following discussion will consider the merits of these heat source concepts.

Geothermal Gradient Heat Source

The geologic setting and physical characteristics of the Corwin Springs-Gardiner thermal features bear strong resemblance

to those of other hot springs in western Montana. Kaczmarek (1974) describes a distinctive group of hot springs in western Montana that all show base reservoir temperatures between 100° C and 120° C. He maintains on the basis of consistent base temperatures and the usual location of the springs on deep fracture zones or steeply inclined permeable rock units that the spring waters all circulate to depths of about 10,000 feet where they acquire heat from warm country rock by conduction. A normal geothermal gradient of 1°C/100 ft., estimated by Chadwick and Kaczmarek (1975) for western Montana, should impart a base level temperature of 107° C to waters circulating to 10,000 feet and, therefore, account for the base temperatures observed at La Duke Hot Spring.

The circulation model for the Corwin Springs-Gardiner thermal system, developed in the preceding chapter, describes the transport of meteoric water to depths as great as 10,000 feet below the surface. Based on a normal geothermal gradient, at this depth water should acquire temperatures near 100° C. Unpublished base temperatures for La Duke Hot Spring, as determined by R. A. Chadwick (personal communication, 1976) using the silica geothermometer method (Fournier and Truesdell, 1970) are:

	Dissolved Silica (ppm)	Estimated Base Temperature (°C)
June, 1973	30.8	81
February, 1975	86.8	131

These temperatures provide reasonable supporting evidence for heating by deep circulation in a region of near normal geothermal gradient considering the expectable seasonal variations in dilution of the spring waters as well as possible errors in sampling and silica determination.

Shallow Magmatic Heat Source

The proximity of the rhyolitic magma body beneath the Yellowstone caldera, some 25 miles south of Gardiner, Montana, raises the possibility of a shallow magmatic heat source for the Corwin Springs-Gardiner thermal system. The magma body is thought to lie between five and ten kilometers beneath the surface (Smith et al, 1974). The occurrence of several young rhyolitic vents, along with geophysical data, suggests that a satellite magma body or perhaps a prong of magma may lie beneath the Sepulcher graben as far north as Gardiner (Eaton et al, 1975). Rhyolite domes as young as 70,000 years intrude the Sepulcher graben between Norris Geyser Basin and Mammoth Hot Springs (Figure 9).

Eaton et al (1975) present a complete Bouguer gravity map that depicts a large gravity low bounded by the closed -210 mgal contour (Figure 9). This contour surrounds the Yellowstone caldera and outlines a relatively narrow low gravity corridor extending north to Corwin Springs from Norris Geyser Basin on the rim of the

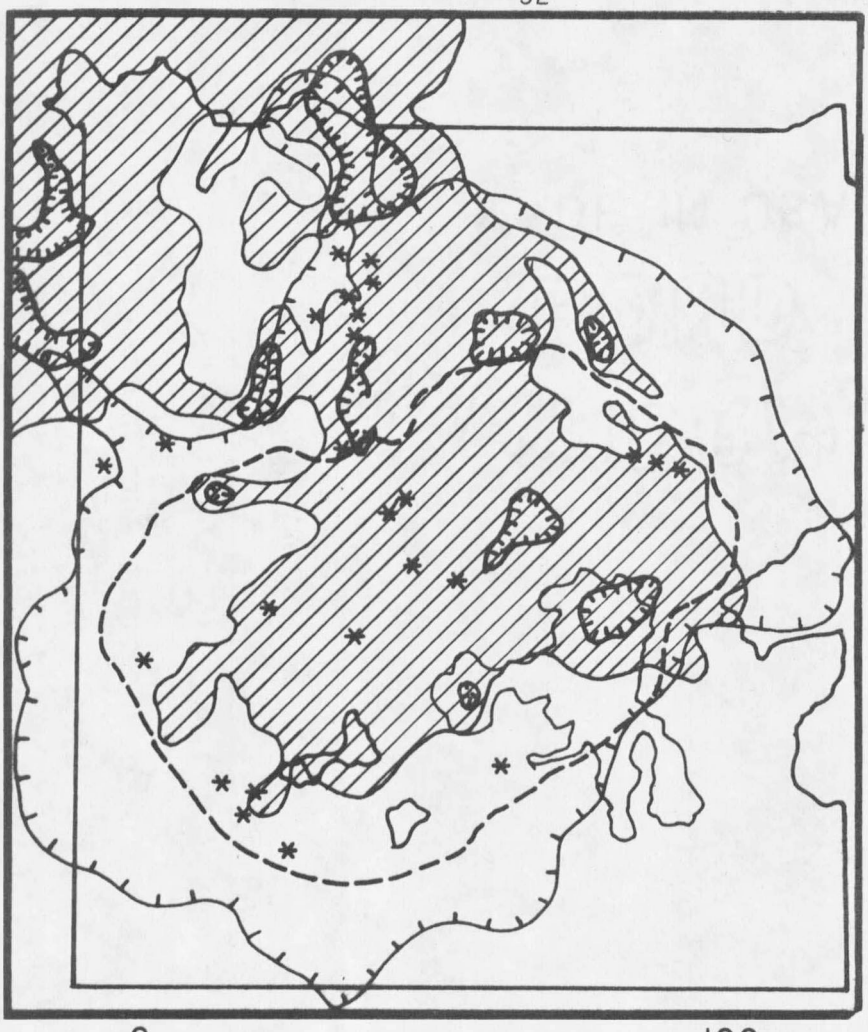


FIGURE 9. COMPILATION OF GEOPHYSICAL ANOMALIES IN THE YELLOWSTONE PARK AREA(modified from Eaton et al., 1975)

caldera. The gravity low is thought to be a composite representation of the Yellowstone rhyolite magma and its crystallized portion, foundered crystalline and sedimentary materials, and hydrothermally altered zones associated with geothermal systems. The gravity field produced by these materials stands in contrast to the gravity highs produced by adjacent crystalline basement rocks.

Changes in the behavior of seismic waves passing through the low gravity area similarly outline the caldera and proposed magma body at depth. The east-west zone of high seismic activity passing through Hebgen Lake ends abruptly at the west edge of the gravity low near the East Gallatin fault (Eaton et al, 1975) (Figure 10). Seismic activity is generally less intense throughout the caldera and Norris-Corwin Springs corridor. Maximum focal depth in the caldera is five km in contrast to greater focal depths outside the caldera. P-waves are attenuated as they pass through the caldera, whereas S-waves are commonly absent or poorly defined.

Negative residual aeromagnetic anomalies also highlight the Yellowstone caldera and the Norris-Corwin Springs corridor (Eaton et al, 1975) (Figure 9). The extensive volumes of hydrothermally altered rock within these areas are interpreted as partly responsible for this magnetic anomaly. A large body of magma or a crystalline pluton beneath the caldera could also account for the broad magnetic

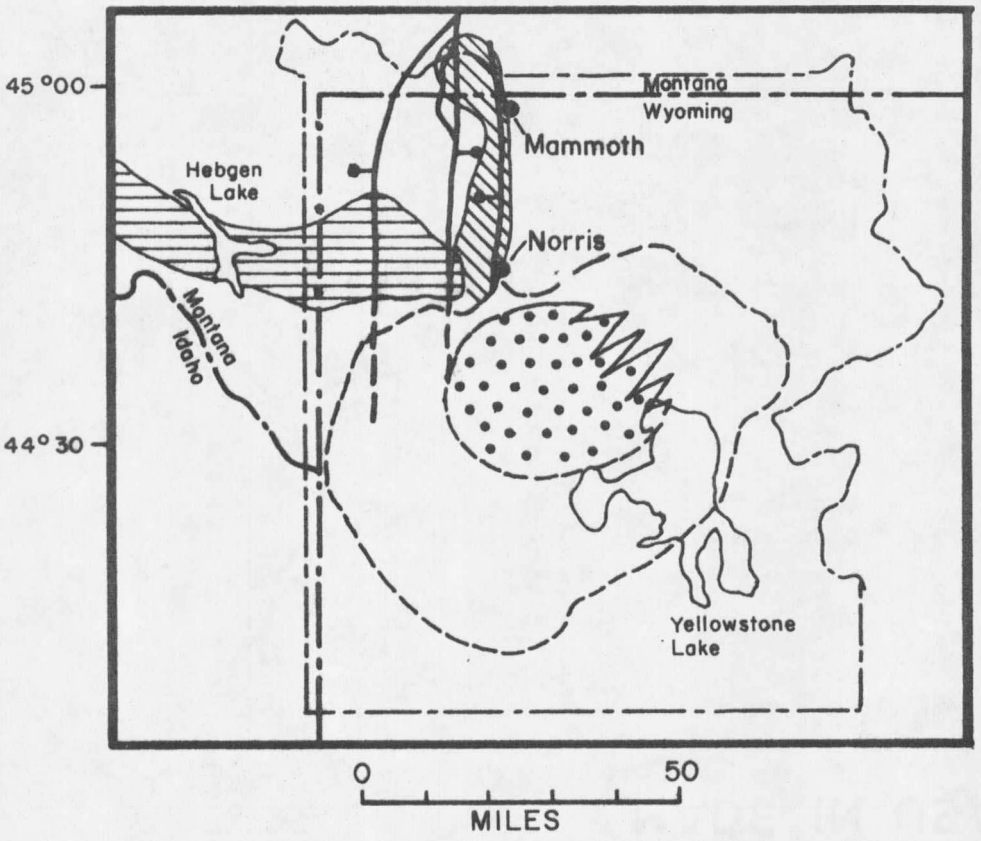


FIGURE 10 SEISMICITY AND SEISMIC ATTENUATION COMPARED TO QUATERNARY FAULT AND VOLCANIC STRUCTURES IN YELLOWSTONE NATIONAL PARK
(modified from Eaton et al, 1975)

low. Surrounding areas underlain by crystalline basement and vent facies of the Eocene volcanics display higher magnetic intensity.

Although the data summarized here are consistent with the existence of magma at depth beneath the Yellowstone caldera and the Norris-Corwin Springs corridor, they are not conclusive. The geologic form and eruptive history of the Yellowstone caldera lend solid support to the geophysical models that depict a shallow magma body within its confines. However, the Norris-Corwin Springs corridor, particularly at its northern end, does not offer such convincing geologic evidence in support of the geophysical data. Quaternary volcanic vent and collapse features are lacking north of Mammoth. The high intensity of geothermal activity associated with the magmatic heat source within the caldera does not appear in the Corwin Springs-Gardiner thermal system. The production of travertine and the lower estimated base level temperatures observed in the Corwin Springs-Gardiner area are characteristic of less vigorous geothermal systems, possibly heated by remnant heat emanating from recently crystallized intrusives or by conduction of heat to deeply circulating water from hot country rock (Chadwick and Kaczmarek, 1975).

Alternative explanations may be applied to the geophysical anomalies observed in the Norris-Corwin Springs corridor. The shallow gravity low in this area may be due to the density contrast between Cretaceous sedimentary rocks and crystalline basement rocks

in nearby uplifted blocks preserved within the Sepulcher graben (Eaton et al, 1975). Bonini (1972) lists assumed average densities of 2.40 g/cc for Cretaceous sedimentary rocks and 2.67 g/cc for crystalline Precambrian rocks. A local negative closure around Gardiner may be caused by the thickened section of sedimentary rock at that locality which is due in part to overturning of the section by reverse faulting. The same exaggerated thickness of sedimentary rocks may produce the residual magnetic low recorded for that area due to the lack of iron-rich minerals in those rocks. An insufficiently long period of study may explain the observed absence of seismic activity in this narrow belt. Surficial evidence produced by Ruppel (1972) indicates that faults have been active within the Sepulcher graben during Pleistocene and Holocene time. The lack of seismic data prevents the construction of a viable model for the bedrock structure in the Norris-Corwin Springs corridor.

The preceding arguments weaken the case for a shallow magmatic heat source in the immediate vicinity of Gardiner. Deep circulation of groundwater is probably the primary means of heating the waters feeding the Corwin Springs-Gardiner thermal system. However, the winter silica geothermometer reading of 131^{o} C for La Duke Hot Spring suggests that the Yellowstone magma body may be close enough to enhance the regional geothermal gradient in the Corwin Springs-Gardiner area. Hot water circulating northward from

the Yellowstone caldera along the Mammoth and East Gallatin faults may also increase the local geothermal gradient. But, the fault zones must be permeable enough to transport quickly large quantities of water to the Corwin Springs-Gardiner system before the water cools significantly.

Chapter 5

POTENTIAL THERMAL ACTIVITY AT DEPTH IN ADJACENT AREAS

The continuation of the Gardiner fault zone to the northwest of Cinnabar Mountain may permit the extension of the Corwin Springs-Gardiner thermal system in that direction. Fault patterns northwest of Cinnabar Mountain suggest that displacement along the Gardiner fault and associated transverse north-trending normal faults forms a graben similar to the Sepulcher graben. A modification of the model proposed herein for the circulation of water in the Corwin Springs-Gardiner thermal system may also describe possible geothermal activity at depth near Cinnabar Basin and Mol Heron Creek (Figure 11). However, the extent and the very existence of such thermal activity is uncertain due to the lack of surficial manifestations of recent geothermal activity. A thick cover of Eocene extrusives probably obscures any near-surface thermal phenomena.

The major structural elements comprising the model for thermal water circulation in the Corwin Springs-Gardiner area also appear on the west side of the southern Gallatin range. The Gallatin anticline extends northwestward from the Gallatin horst to the Madison Range (Ruppel, 1972). Normal displacement along the West Gallatin fault has depressed the crest of the anticline at least 2,500 feet to the west of the horst (Ruppel, 1972) (Figure 11). The Madison

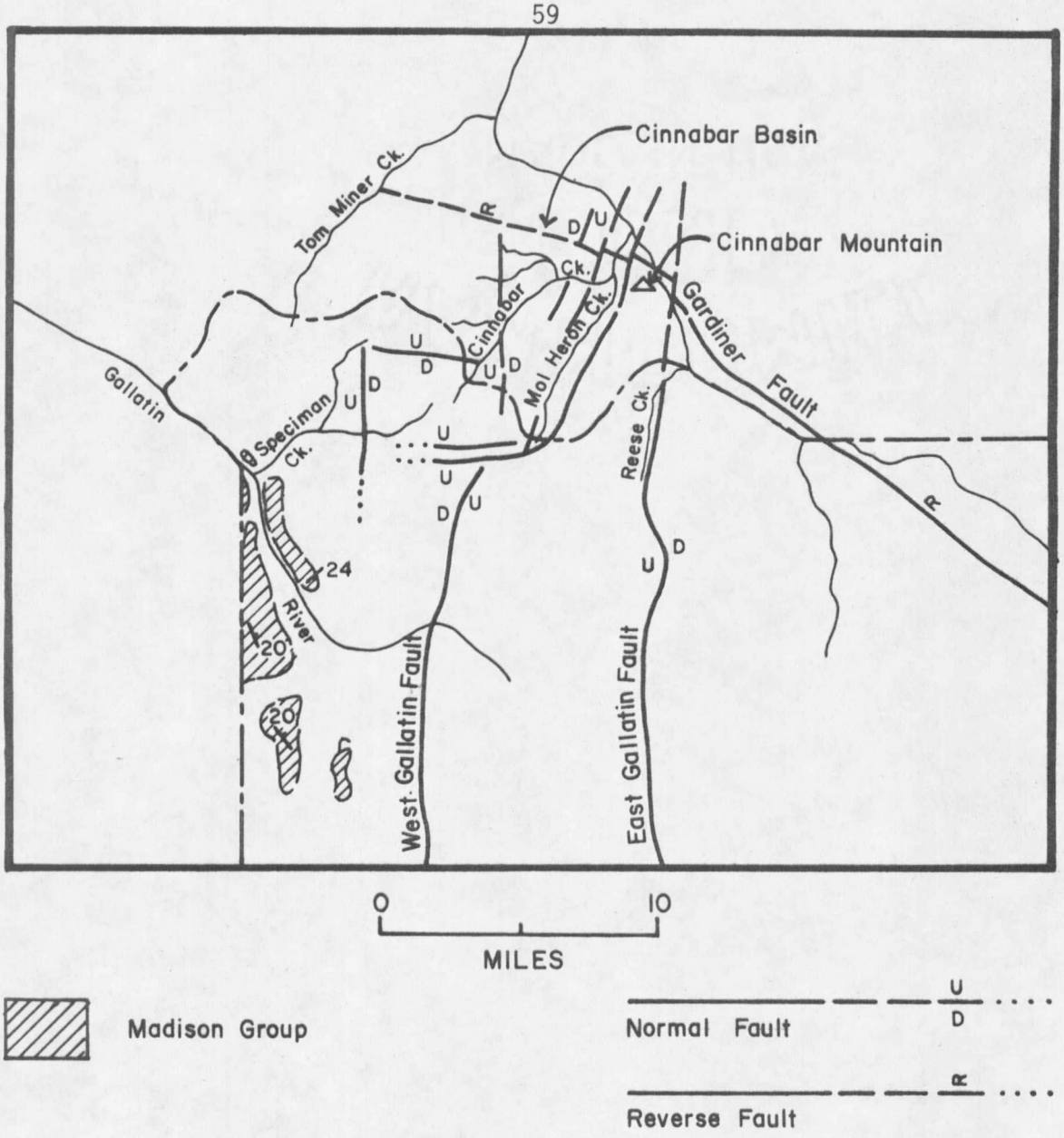


FIGURE II. SKETCH MAP OF THE CINNABAR BASIN AREA : MAJOR FAULTS AND MADISON GROUP EXPOSURES (modified from Fraser, 1969, Ruppel, 1972, and U.S. Geological Survey Map I-711, 1972)

Group crops out along both sides of the Gallatin River upstream from its confluence with Specimen Creek (Figure 11). This unit dips generally to the northeast down the northern limb of the anticline. Several small diversely oriented folds disturb the general dip of the Madison.

These beds are probably dragged up into an asymmetrical syncline as they enter the northwest extension of the Gardiner fault zone beneath Cinnabar Basin although there is no surficial evidence for this. A swarm of northwest trending dacite dikes and fractures which cut Precambrian granitic gneiss identify a portion of the fault zone as it disappears beneath Eocene volcanics on the northwest wall of the Cinnabar Creek gorge. The Gardiner fault probably passes under the northern margin of Cinnabar Basin and reappears to the northwest as the Spanish Peaks fault (Ruppel, 1972). The Mol Heron Creek fault and numerous nearly vertical northeast trending fractures cut the Eocene volcanic cover and control the graben structure to the northwest of Cinnabar Mountain (Figure 11). Apparent left-lateral displacement of the dike swarm by the Mol Heron Creek fault provides evidence for the offset of the Gardiner fault zone and the existence of a graben structure beneath Cinnabar Basin.

As described in the Corwin Springs-Gardiner model, water could flow to considerable depth through joints in the Precambrian hanging wall block of the Gardiner fault though the volcanics covering

much of this structure may impede downward flow. Water may also flow down the Mission Canyon aquifer from the Gallatin River drainage into the Gardiner fault zone beneath Cinnabar Basin.

Several structural features could obstruct this flow pattern. The small folds on the northern limb of the Gallatin anticline may trap water within the Mission Canyon relatively high on the anticline. Several east-west trending normal faults in the vicinity of Specimen Creek could offset the confined Mission Canyon aquifer and similarly trap descending water. Vertical displacement is less along the Mol Heron fault than that along the Reese Creek fault suggesting that the depth of the Mission Canyon is not as great as that in the Sepulcher graben. Even if flow within the Mission Canyon is unimpeded, the depth attained by the water beneath Cinnabar Basin may be significantly less than that attained by water in the Corwin Springs-Gardiner system.

Seismic activity along the Gardiner fault zone in the Cinnabar Basin area is weak (Eaton et al, 1975; Smith et al, 1974). Surficial evidence for recent faulting, contemporaneous with that at Little Trail Creek, is lacking. These facts suggest that the Gardiner fault and the transverse normal faults in Cinnabar Basin may be sealed and impermeable. The sealed condition of the faults explains the absence of thermal springs at the surface in Cinnabar Basin.

Chapter 6

SUGGESTED FUTURE STUDY

A more complete understanding of the Corwin Springs-Gardiner thermal system would require further examination of bedrock geology and thermal features by means of geophysical and geochemical techniques. Several suggestions for clarifying or strengthening the thermal water circulation model deduced from mapping data are presented here.

Reservoir Temperatures

Chemical geothermometers should be applied to effluent samples from La Duke Hot Spring and Bear Creek warm spring to determine their base temperatures at depth. A mixing model using the silica geothermometer method as described by Fournier and Truesdell (1974) should be used because dilution of these thermal waters by cold groundwater from the Yellowstone River valley is highly likely. Joints described in the recharge model developed for the Corwin Springs-Gardiner thermal system may allow descending cold water to mix at great depths with rising thermal water in the Gardiner fault zone. Cold water in near surface alluvium and colluvium may also dilute thermal water at shallow depths. The degree of dilution varies with the seasonal level of runoff in the Yellowstone River drainage. Runoff is normally highest during June and July and decreases during

the rest of the year to its lowest level in February and March. Samples taken during the winter months should yield the highest temperatures as indicated by the preliminary set of samples (Chadwick, personal communication, 1976) referred to in Chapter 4.

Aquifer Rock Type

Dissolved cations and anions in the hot spring effluent may qualitatively verify the role of the Mission Canyon Limestone as a recharging aquifer for the Corwin Springs-Gardiner thermal system. The high dissolved calcium content of the water suggests a limestone aquifer, but the calcium cannot be traced directly to the Mission Canyon Limestone by known geochemical methods. However, high values for $SO_4^=$ and Na^+ are quoted by Taylor (1975, unpublished report) from Fournier (written communication). These data indicate that solution of evaporite beds in the Mission Canyon may be occurring at present (D. L. Smith, personal communication, 1976). Solution breccias, which are probably forming due to the removal of evaporite minerals, contain zones of high porosity. The Na^+ and $SO_4^=$ values cited above are based on an uncertain number of samples and should be verified by additional sampling. Whether these values are anomalous should be ascertained by comparison with values from spring waters originating in nearby crystalline basement rocks. Since natural cold springs are scarce in the vicinity of La Duke Hot

Spring, water wells should be considered for sampling. Residents in section 5, T. 9 S., R. 8 E., immediately south of La Duke Hot Spring, and in section 14, T. 9 S., R. 8 E., southeast of La Duke Hot Spring, may have wells that tap water draining from the Precambrian terrain of Sheep Mountain.

Character of Structure and Lithology at Depth

The gravity survey of Yellowstone National Park and vicinity referred to in Chapter 4 locates a gravity low in the Corwin Springs-Gardiner area. The gravity data suggest that the Yellowstone River valley in this area may be underlain by a great thickness of sedimentary rocks, a hydrothermally altered zone, or a magma body. A detailed gravity survey of the valley between Corwin Springs and Bear Creek may help determine the nature of the bedrock and fault zones within the valley and improve Eaton's subsurface model for northwestern Yellowstone Park.

A detailed knowledge of the vertical and lateral extent of the Gardiner travertine deposits would assist in the identification of fractures formerly controlling the outflow of thermal water. Active seismic techniques could readily distinguish the base of the travertine lying on the Pliocene-Pleistocene basalt and produce data suitable for making an isopach map of the travertine deposit. The isopach map and outcrop observations could provide evidence for the

migration of springs with time due to tectonic activity or sealing of conduits.

Seismicity of the Corwin Springs-Gardiner Area

Passive seismic monitoring of the Corwin Springs-Gardiner area is necessary to determine the seismicity of the fault zones controlling the local thermal system. The permeability of the fault zones is dependent upon the frequency and intensity of movements along the fault zones. Recurrent tectonic movement is probably needed to prevent sealing of the thermal water conduits by the deposition of travertine from the calcium-rich thermal water. Low seismicity in the area may be responsible for the present inactivity of the springs that built the Gardiner travertine terraces. Micro-earthquake activity should be monitored since such seismicity is generally associated with vigorous thermal systems (Comb and Muffler, 1973). Microseisms probably result from continual movements along faults within the thermal system.

Concealed Thermal Water Sources

Considerable thermal water may escape into the Yellowstone River drainage from sources hidden beneath surface material in the vicinity of the active springs and elsewhere along the Gardiner fault zone. Electrical and electromagnetic techniques that measure the

electrical resistivity of materials at depth could be used to attempt to determine the true extent of the hot spring system from the surface to depths as great as two miles (Combs and Muffler, 1973). Rock bodies that are saturated with thermal water should show distinctively low electrical resistance. These methods could be used to produce three dimensional models of the thermally active zones. Numerous traverses across the Gardiner fault zone between Bassett Creek and Little Trail Creek would help define the real extent of near-surface outflow patterns of the La Duke Hot Spring thermal area.

An assessment of present thermal activity and the energy production potential of the thermal system would benefit most from the recommended geochemical, passive seismic, and electrical or electromagnetic resistivity techniques. These techniques could help locate and define the margins of active hydrothermal zones at depth.

Chapter 7

SUMMARY AND CONCLUSIONS

The Corwin Springs-Gardiner geothermal system, including La Duke Hot Spring and Bear Creek warm spring, resembles many of the geothermal systems scattered throughout western Montana in its similar geologic setting and type of heat source. The water circulating in this distinct group of geothermal systems is thought to derive heat by descending to great depths along fracture zones or permeable rock units where it reaches thermal equilibrium with the country rock that is warmed by the local thermal gradient. These geothermal systems, including the Corwin Springs-Gardiner system, are to be distinguished from the Yellowstone system that obtains heat from a shallowly emplaced magma body.

Chadwick and Kaczmarek (1975) classify Montana thermal systems in four distinct types according to their particular recharge mechanisms. These types include: (1) warm springs in carbonate rock, (2) hot springs in valley fill overlying fractured or porous bedrock, (3) hot springs in fractured, crystalline bedrock, and (4) hot springs fed from deep, confined aquifers. A combination of the latter two types of thermal systems probably describes recharge and circulation in La Duke and Bear Creek warm springs.

The thermal waters sustaining La Duke and Bear Creek springs rise along the northwest-trending Gardiner fault zone and emerge from

fractures where the north-trending Reese Creek and Mammoth normal faults intersect the Gardiner fault. Ascending thermal water is, in part, replaced at depth by groundwater that percolates downward through joints in the Precambrian granitic gneiss of the Gardiner fault hanging wall block. The groundwater is heated at depth by conduction from the country rock and is displaced upward into open fractures in the Gardiner fault zone by the denser cold water descending from above.

Perhaps an even greater supply of meteoric water flows down a cavernous aquifer within a Late Mississippian paleokarst zone of the Mission Canyon Limestone. The Mission Canyon aquifer dips gently to the north under the steeply north-dipping Gardiner fault zone from the crest of the northwest-trending Gallatin anticline within Yellowstone National Park. The aquifer probably attains a depth of 10,000 feet within the Sepulcher graben where it intercepts the Gardiner fault zone. Water heated at this depth then ascends the fault zone.

Base temperatures for La Duke Hot Spring, as determined by the silica geothermometer method, range from 81^{o} C in the summer, to 130^{o} C in the winter. If the local thermal gradient approximates the regional average of 1^{o}C/100 feet for western Montana, it may supply sufficient heat to produce base temperatures near 100^{o} C in water that circulates to a depth of 10,000 feet. High summer water levels in the Yellowstone River drainage probably cause considerable

dilution of the thermal waters and lower the calculated base temperatures. Therefore, the winter base temperature values are probably more reliable. However, the winter base temperatures of 131° C exceeds the value expected from the regional average thermal gradient which is 1°C/100 feet. Thus, heat is probably obtained from an additional source. The proximity of the Yellowstone magma body about 25 miles to the south of Gardiner may cause an anomalous steepening of the thermal gradient leading to the observed winter base temperature value. The base temperature indicates a thermal gradient of 1.25°C/100 feet.

Hot spring activity in the Corwin Springs-Gardiner system appears to be declining from that intensity of flow which produced the Gardiner travertine terraces. Inactivity of the Gardiner fault in recent centuries and the sealing of fracture conduits by the deposition of travertine are the probable causes for this decline. A decrease in the supply of water recharging the system may also have developed as the climate became drier at the close of the Pleistocene, with resulting decreased discharge.

The Corwin Springs-Gardiner thermal system does not offer much promise as an electrical power source using current technology. Base temperatures indicate that the thermal system cannot generate sufficient steam to drive turbines of the type used to produce electricity in geothermal plants now operating. These power plants

require reservoir temperatures in excess of 150° C for efficient power production (White, 1973). Technological advances may allow utilization of thermal waters ranging in temperature from 100° C to 150° C for electric power generation (Chadwick and Kaczmarek, 1975). However, the thermal waters may be most effectively used to heat buildings or greenhouses in the Corwin Springs-Gardiner vicinity. Shallow drilling may reveal additional hot water sources along the Gardiner fault zone.

APPENDIXES

APPENDIX A

GENERALIZED STRATIGRAPHIC SECTION: GARDINER REGION

The following section is generalized from sections measured by Wilson (1934b), Fraser et al (1969), and Ruppel (1972) at Cinnabar Mountain, Mount Everts, and the southern Gallatin Range.

CRETACEOUS

Landslide Creek Formation: about 2,000 feet thick, gray, poorly sorted sandstone and conglomerate made up principally of andesitic fragments.

Everts Formation: about 1,200 feet thick, fine-grained, tuffaceous salt and pepper sandstone with interbedded gray shale.

Eagle Sandstone: about 800 feet thick, massive, calcareous, salt and pepper sandstone with thin interbedded shale and coal.

Telegraph Creek Formation: about 300 feet thick, light-gray, fine-grained calcareous sandstone and interbedded gray shale.

Cody Shale: about 1,200 feet thick, dark-gray shale, bentonite beds, and thin brownish-gray dirty sandstone beds.

Frontier Sandstone: 40-60 feet thick, gray-brown, well-sorted, salt and pepper sandstone.

Mowry Shale: 300-320 feet thick, hard, black sandy shale, interbedded sandstone, and bentonite.

Thermopolis Shale: 390-500 feet thick, dark-gray fissile shale and interbedded sandstone and siltstone.

Kootenai Formation (Cloverly equivalent): 250-400 feet thick, coarse, chert-pebble conglomerate and massive salt and pepper cherty sandstone, gray, fissile shale, and light-gray limestone.

JURASSIC

Morrison Formation: 200-320 feet thick, grayish-red, dark-gray, and grayish-green partly calcareous shale, mudstone, siltstone, and sandstone.

Ellis Group:
- Swift Formation: 15-60 feet thick, brown to gray calcareous sandstone and limestone.
- Rierdon Formation: 40-60 feet thick, oolitic limestone, red siltstone, mudstone, and shale.
- Sawtooth Formation: 140 feet thick, limestone, red to gray siltstone, mudstone, and shale.

TRIASSIC

Thaynes Formation: 15-20 feet thick, gray, calcareous sandstone.

Woodside Formation (Chugwater equivalent): 75-100 feet thick, red siltstone, shale, and sandstone.

Dinwoody Formation: 0-80 feet thick, white, porous, thinly bedded limestone.

PERMIAN

Shedhorn Sandstone (Phosphoria): 115-160 feet thick phosphatic, cherty sandstone.

PENNSYLVANIAN

Quadrant Sandstone: 130-300 feet thick, light brown orthoquartzite with some dolomite.

Amsden Formation: 20-160 feet thick, red calcareous or dolomitic siltstone, shale, or sandstone.

MISSISSIPPIAN

Madison Group:
- Mission Canyon Limestone: 800 feet thick, massive fossiliferous limestone with dolomite and dolomite breccia zones.
- Lodgepole Limestone: 480 feet thick, thinly-bedded, fossiliferous, cherty limestone.

DEVONIAN

Three Forks Formation: 80-120 feet thick, interbedded shale and limestone.

Jefferson Formation: 120-240 feet thick, brown, fetid limestone and dolomite.

ORDOVICIAN

Bighorn Dolomite: 80-130 feet thick, massive dolomite and limestone.

CAMBRIAN

Snowy Range Formation: 110-300 feet thick, interbedded shale, sandstone and limestone.

Pilgrim Limestone: 160-300 feet thick, dolomitic limestone.

Park Shale: 90-120 feet thick, grayish-green shale.

Meagher Limestone: 140-400 feet thick, thinly bedded limestone.

Wolsey Shale: 80-200 feet thick, greenish-gray sandy shale.

Flathead Sandstone: 40-160 feet thick, quartzitic sandstone.

PRECAMBRIAN

Granitic gneiss, schist, amphibolite.

APPENDIX B

DESCRIPTION OF EOCENE DACITES AND ANDESITES

Distribution

Exposures of Eocene dacitic and andesitic extrusives and intrusives are common in the vicinity of the Corwin Springs-Gardiner hot spring systems. These rocks are important to the interpretation of Laramide structure and chronology that affect the occurrence of the local thermal features.

Thick piles of dacitic and andesitic flows and breccias are preserved in the Sepulcher graben, on the Beartooth block, and in the Cinnabar Basin area. The Sepulcher volcanics probably erupted from the Electric Peak stock (Iddings, 1891), whereas the Cinnabar Basin units may have erupted from any of a number of vents scattered along the Gallatin Range, the Beartooth block, and the Yellowstone River valley northward from Electric Peak. These volcanics occupy a portion of the western belt of eruptive centers known as the Absaroka-Gallatin Volcanic province, which extends from the southern end of the Absaroka Range in Wyoming, to the northern end of the Gallatin Range in Montana (Chadwick, 1970).

A number of dikes and small stocks lying within the Gardiner fault zone may be included in the group of vents postulated for the Absaroka-Gallatin volcanic province, though their contribution to

the extrusive pile is probably minor (Fraser et al, 1969). These intrusions presumably shared a common magma source with the major centers of eruption in the area, but selectively followed the Gardiner fault zone during the latter part of their ascent to the surface. The dikes range from several inches to 200 feet wide. They are best exposed as a swarm striking northwesterly with a steep northeast dip between Little Trail Creek and Cinnabar Creek. This swarm of dikes may extend northwest toward the Spanish Peaks extension of the Gardiner fault, under the Eocene extrusive cover of the northern Gallatin Range. The dike swarm probably intersects the trend of the Western Absaroka Belt (Chadwick, 1970) of Eocene volcanic centers in the vicinity of Tom Miner Basin. The Western Absaroka Belt extends south of the Gardiner fault zone through Electric Peak and Mount Washburn in Yellowstone National Park. The dikes trend to the southeast under the Pliocene-Pleistocene basalts covering the Gardiner fault zone north of Gardiner (Figure 4, page 23), and reappear at Bear Creek where the Gardiner fault is exposed.

Several small dacitic stocks have intruded the hanging wall of the Gardiner fault between Little Trail Creek and Cinnabar Creek. The intrusions seem to be restricted to within one mile of the fault zone. The Tom Miner and Cinnabar intrusives identified by Shaver (1974) may intrude the hanging wall of the covered northwest extension of the

Gardiner fault in a similar fashion. Remnant patches of dacitic flows, flow breccias, and volcanic sediments lie on slopes to the northeast of the Gardiner fault zone above Corwin Springs. These exposures may be, in part, the extrusive products of the aforementioned vents.

Petrography

Those Eocene intrusive rocks which exploited the Gardiner fault zone may be categorized into three distinct groups according to their mineralogy. These groups include a biotite dacite, a hornblende-biotite dacite, and a hornblende-biotite andesite. The groupings presented here are based on average mineral percentages observed in hand sample and in thin section. The variations in mineralogy represent gradations of a fundamental magma. In addition, chilling near dike margins may produce fine grained textural variations. These rock types are distinguished as follows.

Biotite Dacite

Biotite dacite outcrops in dikes along the Gardiner fault zone on the northern shoulder of Cinnabar Mountain west of Corwin Springs and also as a plug on the west facing slopes of Sheep Mountain above Corwin Springs and La Duke Hot Spring (Figure 4, page 23). This dacite contains phenocrysts of calcic andesine and oligoclase, biotite, quarts, and magnetite or pyrite (Plate 11). The plagioclase

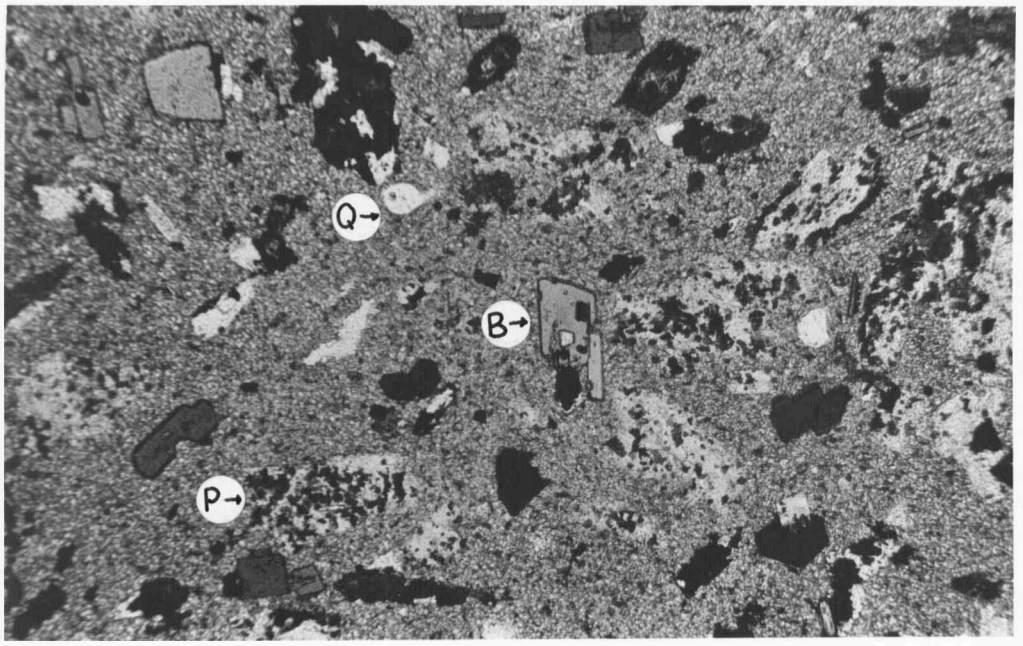


PLATE 11. Photomicrograph of biotite dacite from dike .25 miles east of La Duke Hot Spring; quartz (Q), plagioclase (P), biotite (B) (nicols uncrossed).

forms 0.5 to 3 mm euhedral and broken grains, some of which show oscillatory and patchy zoning. A few zoned phenocrysts are altered to sericite and calcite. The biotite grains are fresh, euhedral flakes 1 to 2 mm across. Quartz forms rounded and embayed phenocrysts up to 2 mm across. Small anhedral aggregates up to 0.5 mm across appear in the groundmass. Phenocrysts of hornblende occur but are quite scarce. Small euhedral to subhedral magnetite and pyrite grains are scattered throughout the groundmass. Hematite and other iron oxides form rims on some biotite phenocrysts. The groundmass is generally a pilotaxitic mixture of K-feldspar, quartz, plagioclase microlites, glass and ore. A few specimens exhibit aplitic textured groundmasses. This dacite outcrops in an autobrecciated form with dacite fragments, as described above, resting in a hematitic glass matrix. Both the dacite and the autobreccia contain random clasts of Precambrian granitic gneiss and sericitic schist.

Hornblende-Biotite Dacite

The hornblende-biotite dacite appears in one dike on the north flank of Cinnabar Mountain, and in a small stock one mile north of Corwin Springs on west facing slopes of Sheep Mountain. This dacite also comprises the flows and tuffs which lies unconformably above biotite dacite intrusives northeast of Corwin Springs (Figure 4, page 23). The hornblende-biotite dacite includes phenocrysts of

calcic plagioclase, biotite, hornblende, quartz, and magnetite (Plate 12). The plagioclase forms 0.5 to 5 mm euhedral grains and fragments showing pervasive oscillatory and patchy zoning. Pericline twinning is also common. The phenocrysts are in part altered to sericite and calcite. Biotite grains are fresh euhedral flakes 1 to 2 mm across. Hornblende forms broken, corroded phenocrysts, and a few fresh euhderal grains. Some hornblende phenocrysts are partly altered to biotite. Opaque rims appear on some phenocrysts. Many of the phenocrysts are completely altered to hematite and calcite. Quartz forms subhedral, rounded or embayed phenocrysts up to 1 mm across, as well as small aggregates of anhedral grains within the groundmass. Quartz is scarce in some specimens. Small euhedral magnetite grains are disseminated throughout the groundmass. The groundmass is generally a pilotaxitic mixture of K-feldspar, quartz, plagioclase microlites, glass, and ore. A few clasts of granitic gneiss and biotite dacite appear along with fragments of hornblende-biotite dacite. Autobrecciation is not as well developed as in the biotite dacite.

Hand samples of hornblende-biotite dacite display phenocrysts of plagioclase, biotite, and hornblende in a gray groundmass. Visible quartz phenocrysts are rare. Casts of hornblende phenocrysts are quite abundant on weathered surfaces. Green and orange discoloration of the plug north of Corwin Springs suggests fumarolic or hydrothermal

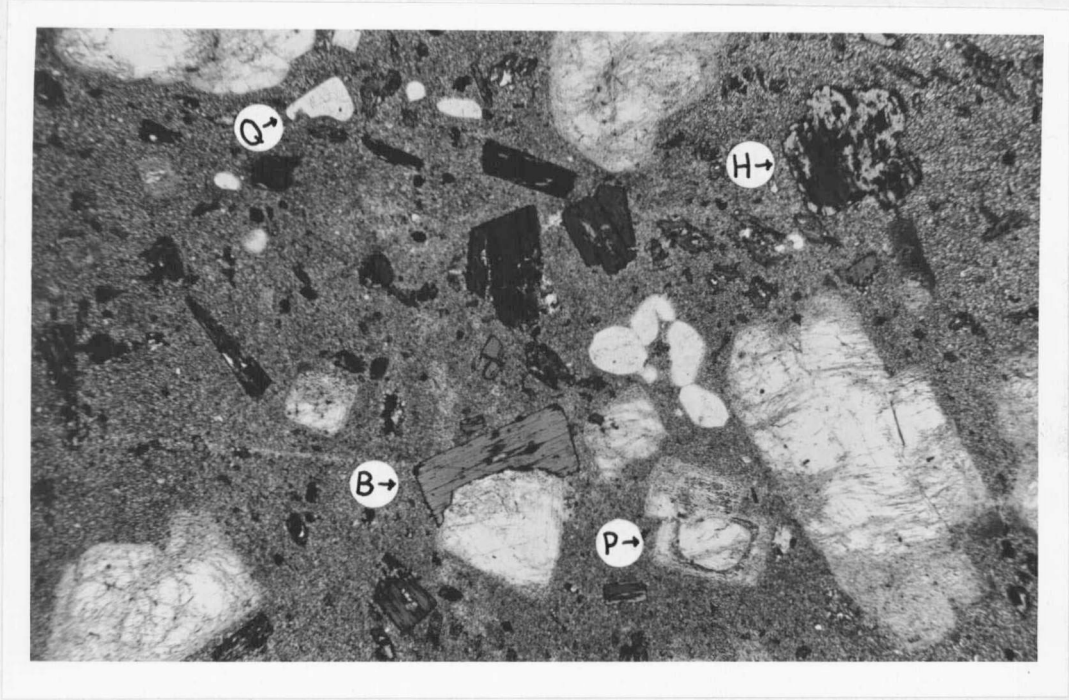


PLATE 12. Photomicrograph of hornblende biotite dacite from dike .5 miles west of Corwin Springs on Cinnabar Mountain; Quartz (Q), plagioclase (P), hornblende (H) altering to biotite, biotite (B) (nicols uncrossed).

activity. Green montmorillonite, chlorite, and iron oxides may produce these colors.

Hornblende-Biotite Andesite

The hornblende-biotite andesite occupies scattered dikes and small stringers within the Gardiner fault zone and its hanging wall. Some flow material similar to this intrusive lies on the west facing slopes of Sheep Mountain, uphill from Corwin Springs (Figure 4, page 23). However, the source of this rock may be one of the more prolific andesitic vents described by Fraser et al (1969) on the Beartooth block to the east. The hornblende-biotite andesite contains phenocrysts of labradorite plagioclase, hornblende, biotite, augite, and magnetite (Plate 13). A few small quartz grains are also visible. Plagioclase ranges from andesine to labradorite in compositon and forms 0.5 to 2 mm euhedral phenocrysts that exhibit some oscillatory zoning. Overgrowths of sericite and calcite are common. Hornblende forms fresh euhedral laths 1 to 2 mm across as well as scattered crystal aggregates. Hornblende laths may be corroded or altered to iron oxides or calcite. Biotite grains are fresh and euhedral. A few corroded phenocrysts of augite are also present. The groundmass is generally a pilotaxitic mass of plagioclase microlites, anhedral mafic minerals, and ore, along with some K-feldspar and quartz. The

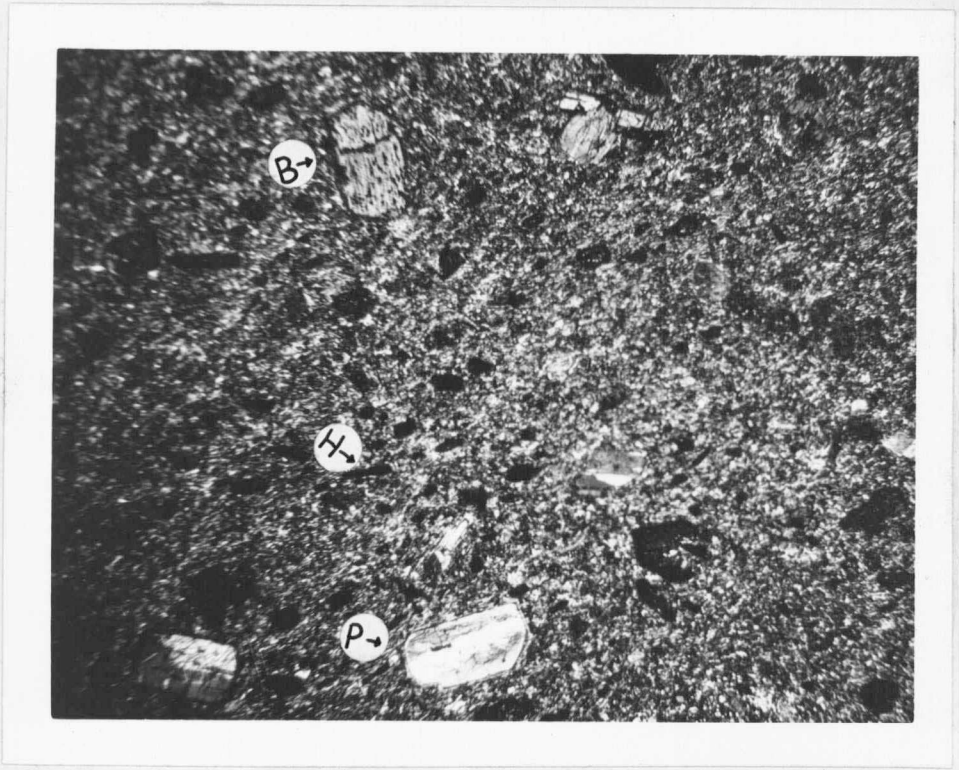


PLATE 13. Photomicrograph of hornblende-biotite andesite showing subtrachytic texture from dike .5 miles north of La Duke Hot Spring; plagioclase (P), biotite (B), hornblende (H) (nicols crossed).

andesite dike exposed west of the Corwin Springs bridge contains clasts of granitic gneiss and biotite dacite.

Hand samples of hornblende-biotite andesite consist of fresh phenocrysts of plagioclase, hornblende, and biotite in a dark gray groundmass. The chilled margins of the dikes are exceedingly fine grained and contain no phenocrysts.

Petrology and Chronology

Petrographically, the three described intrusives are quite similar suggesting that they are comagmatic. The three intrusives are products of normal differentiation of a calc-alkaline magma. Each of these rock types contains plagioclase, hornblende, biotite, quartz, and magnetite or pyrite phenocrysts. However, the proportion of these phenocrysts differs in all three cases. These differences reflect the degree of magmatic differentiation that occurred as each intrusive ascended to the upper crust or surface from its probable source in the upper mantle or lower crust. The abundance of quartz and prevalence of biotite in the biotite dacite, suggest that differentiation progressed further than in the other rock types. Bowen (1928) describes quartz and biotite as late stage differentiates in cooling basaltic magmas. Hornblende has a higher crystallization temperature and commonly appears at an intermediate stage in the differentiation process. Thus, the hornblende-biotite dacite

represents an intermediate stage in the differentiation process. The remnant augite in the hornblende-biotite andesite suggests that crystallization was completed at a yet higher temperature when differentiation was less advanced. The magma that produced these intrusives was probably rich in water as a result of differentiation as well as crustal contamination of the magma during its ascent. The high water content influenced differentiation by lowering the crystallization temperature of all components in the magma.

Cross cutting relationships and recognizable xenoliths provide evidence for the order of emplacement of the described intrusives. These relationships are best observed on the north flank of Cinnabar Mountain about 0.5 miles west of Corwin Springs, where a dike of hornblende-biotite dacite cuts biotite dacite dikes. A few hornblende-biotite andesite dikes up to 20 feet in thickness cut both dacites (Plate 14). The superposition of hornblende-biotite dacite flows on biotite dacite intrusives 0.25 miles northeast of Corwin Springs further support these age relationships. Andesite dikes are clearly the latest intrusives at all localities examined.

Correlation of Intrusives

The mineralogies and textures of the Corwin Springs dacite dikes resemble those of the Cinnabar-Mol Heron and Little Trail Creek dacite intrusives described by Shaver (1974) and suggest that these

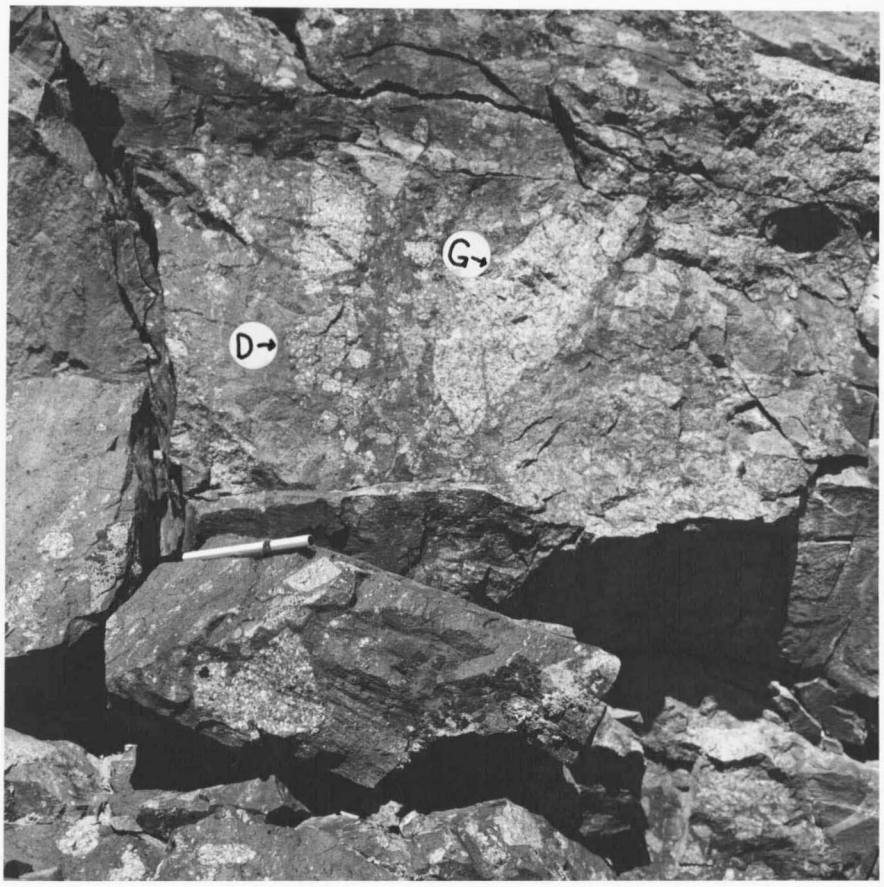


PLATE 14. Andesite dike containing clasts of Precambrian granitic gneiss (G) and biotite dacite (D) about .5 miles west of Corwin Springs.

intrusives are the same age. However, the stratigraphic positions of these intrusives differ. The Cinnabar-Mol Heron dacites appear to cut the andesite breccias filling Cinnabar Basin (Shaver, 1974), whereas the Corwin Springs dacite dikes are probably covered unconformably by the breccias. These breccias have been tentatively identified by Chadwick (personal communication, 1975) as the Golmeyer Creek Volcanics which lie directly on the Corwin Springs dacites and beneath the younger Hyalite Peak Volcanics. Chadwick (1969) suggests that the Golmeyer Creek Volcanics are about 53 million years old. This age, according to Prostka and Smedes (1972), dates the Golmeyer Creek Volcanics as Early Eocene, and therefore dates the Corwin Springs dacite dikes as Early Eocene or older. Since the Gardiner fault does not significantly fracture the Corwin Springs dacite dikes, the latest possible time for major reverse displacement along the Gardiner fault zone is the Early Eocene.

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