1 of 3

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TO ACCOMPANY MAP GP-444

BOUGUER GRAVITY, AEROMAGNETIC, AND GENERALIZED GEOLOGIC MAP OF EAST HELENA AND CANYON FERRY QUADRANGLES AND PART OF THE DIAMOND CITY QUADRANGLE, LEWIS AND CLARK, BROADWATER, AND JEFFERSON COUNTIES, MONTANA

By

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INTRODUCTION

Aeromagnetic and gravity surveys were made in East Helena, Canyon Ferry, and Diamond City quadrangles as part of a broader study of intermontane basins along the upper Missouri River. The work was done primarily to delineate masses of igneous rocks and to determine the configuration of the bedrock surface beneath Cenozoic sedimentary and volcanic deposits that occupy the main valleys. This information was used in conjunction with the results of geologic mapping to interpret buried geologic features and thereby gain a more complete understanding of the regional structure.

The map area lies in parts of Lewis and Clark, Broadwater, and Jefferson Counties in west-central Montana. East Helena quadrangle is only a few miles east of the city of Helena and includes the northern slopes of the Elkhorn Mountains, the broad flat of Prickley Pear basin between the Scratch Gravel and Spokane Hills, and a low range of hills along the northern side of the basin. Canyon Ferry quadrangle contains the Spokane Hills, the northern part of Townsend Valley, and a part of the Big Belt Mountains whose western front continues southeastward into the Diamond City quadrangle. The Missouri River flows northwest across the southern and western parts of Canyon Ferry quadrangle and the northeastern part of East Helena quadrangle. Hauser Lake and Lake Helena, formed by dams on the Missouri River and Prickly Pear Creek, respectively, lie in the northern part of Prickly Pear basin. Lake Sewell, which is a reservoir formed by the Canyon Ferry dam, covers much of the floor of Townsend Valley. Within the area of geophysical study, which does not extend far into the uplands, the surface rises gradually toward the base of the surrounding hills and mountains, where it is about 600 to 800 feet above the basin and valley floors. The intervening Spokane Hills rise some 1,500 feet above the lowlands.

GENERAL GEOLOGY

The following discussion of the geology of the region is taken from reports and maps of Knopf (1913 and in press), Pardee (1925, 1950), Pardee and Schrader (1933), Mertie, Fischer, and Hobbs (1951), Klepper, Weeks and Ruppel (1957), Freeman, Ruppel, and Klepper (1958), Robinson (1959, 1960), Smedes (1960, 1962), and Nelson (1963).

The region is underlain by about 15,000 feet of upper Precambrian, Paleozoic, and Mesozoic sedimentary rocks and several thousand feet of Upper Cretaceous volcanic rocks. These rocks were intruded by hypabyssal bodies of basalt and andesite and were then deformed during a Late Cretaceous (Laramide) orogeny. During latest Cretaceous or Paleocene time, the rocks were intruded and thermally metamorphosed by igneous rocks of gabbroic to granitic composition that are present in satellitic bodies of the Boulder batholith. Subsequently, the Cretaceous and older rocks were faulted and eroded to a mature surface upon which lower and middle Oligocene deposits accumulated. Block-faulting and tilting occurred intermittently during deposition and continued in late Oligocene and (or) early Miocene time; then the region was again deeply eroded (Robinson, 1960, p. B-227). Deposition took place again in later Miocene and Pliocene time, followed by local folding and by renewal or continuation of eastward tilting. The Cenozoic deposits consist of waste from the bordering mountains interbedded with volcanic ash and may be as much as 10,000 feet thick (Knopf, 1913, p. 94; Mertie, Fischer, and Hobbs, 1951, p. 51).

The Big Belt Mountains, which reach an altitude of more than 7,000 feet in the eastern part of the area, are underlain by Precambrian and Paleozoic rocks that form a broad northwest-trending, uplifted arch (Mertie and others, 1951, p. 51). In the central part of the arch that lies in the northeast corner of the area, Precambrian rocks have been thrust-faulted northeastward over Paleozoic rocks. Sedimentary rocks of Cambrian, Devonian, Carboniferous, and Permian age form the mountain front on the northeastern side of Townsend Valley. A major fault zone, considered by Pardee and Schrader (1933, p. 24-25, 129-130) to be a part of the Eldorado thrust, runs along the mountain front and continues northwest across part of East Helena quadrangle. Within this zone the Paleozoic rocks and some of the Precambrian rocks have been deformed into tight folds and cut by high-angle thrust faults (Mertie and others, 1951, p. 51-52). The Precambrian strata are cut by bodies of diorite, gabbro, and andesite which appear to have been intruded before folding, perhaps in Precambrian time (ibid, p. 48). The Precambrian and Paleozoic strata also are cut by latite, monzonite, and granite, which were intruded after folding.

The Spokane Hills are a broad north-trending ridge that lies between Townsend Valley and Prickly Pear nasin. The hills are underlain by Precambrian and Paleozoic sedimentary rocks that have been deformed into a series of north-trending tight folds on the western limb of a general synclinal structure (ibid, p. 53). Several steep faults cut across the strike of the formations at high angles. Stocks of granitic rocks that are thought to be related to the Boulder batholith crop out in the eastern and southern parts of the hills. A monzonite lamprophyre dike and several larger bodies of similar intrusive rocks are exposed along the western slopes.

Precambrian sedimentary rocks of the Belt Series underlie the hills along the northern and western margins of Prickly Pear basin. In the Scratch Gravel Hills north of Helena, these rocks have been cut by a large mass of syenodiorite and small bodies of diorite porphyry and gabbro (Knopf, in press).

The mountains and foothills along the southern margin of Prickly Pear basin are underlain by Precambrian, Paleozoic, and Mesozoic sedimentary rocks, Upper Cretaceous volcanic rocks, and Upper Cretaceous or Paleocene plutonic igneous rocks (Smedes, 1962; Knopf, in press). The sedimentary rocks are complexly folded and faulted. The volcanic rocks are part of the Elkhorn Mountains Volcanics which, in the map area, occupy the northern end of the Elkhorn Mountains. These volcanic rocks consist of breccias, tuffs, lavas, and welded tuffs of andesitic, basaltic rhyodacitic, and quartz latitic composition. The volcanic and older rocks have been intruded by basaltic and andesitic dikes, sills, and irregular masses that are contemporaneous with part of the Elkhorn Mountains Volcanics. These intrusive rocks and all older rocks were deformed and subsequently intruded by igneous masses of syenogabbro, monzonite, diorite, granodiorite, and related rocks that represent early and intermediate stages of intrusion of the Boulder batholith. A satellite body, called the Antelope Creek stock, lies east of the batholith at the south corner of the East Helena and Canyon Ferry quadrangles. The intrusive body shown on the map includes a central stock of granodiorite, segments of an older ring dike of monzonite, and a still-older sheet of porphyritic basalt (Smedes, 1960). Sedimentary and volcanic country rocks are thermally metamorphosed around the margins of the Boulder batholith and the Antelope Creek stock.

Townsend Valley and Prickly Pear basin are areas of low relief underlain by Tertiary deposits consisting mainly of conglomerate, tuffaceous shale and sandstone, and tuff, and minor amounts of breccia, limestone, and diatomaceous earth. Many of these are poorly consolidated or unconsolidated. Throughout much of the area the lowlands are bordered by broad fans and aprons of Pleistocene and Recent alluvium which, in turn, are bordered in many places by low benchlands of Tertiary deposits that are rich in volcanic ash. In Townsend Valley these Tertiary deposits are tilted and form a homocline dipping 10° to 30° northeastward (Mertie and others, 1951, p. 55) and apparently are faulted against older rocks in the Big Belt Mountains. In Prickly Pear basin the structure of the Tertiary deposits is not known.

The pre-Cenozoic sedimentary rocks consist mainly of shale, siltstone, limestone, and sandstone. Densities of well-cemented surface samples of most of these rocks range from 2.58 to 2.86 g per cm^3 as determined by the authors and by Knopf (in press). The shale formations, owing to their weathered condition, were not sampled. They contain thin beds of sandstone and have an estimated average density of about 2.5 g per cm^3. Density determinations made from igneous rock samples indicate that the densities of the volcanic rocks range from 2.4 to 2.7 g per cm^3 and that those of the intrusive rocks range from 2.6 g per cm^3 for granite to 3.2 g per cm^3 for gabbro. These data and the distribution of the sedimentary and igneous rocks suggest that the bedrock of the region probably has an average density of about 2.7 g per cm^3.

Only sparse data were obtained on densities of the Cenozoic sedimentary deposits. Measurements made on samples collected from the more resistant beds showed values of 2.3 g per cm^3 for tuff to 2.4 g per cm^3 for the tuffaceous sandstone and grit, a few samples of which have densities as high as 2.5 per cm^3. The limestone, which is thin bedded and thought to be lenticular and only locally developed (Mertie and others, 1951, p. 37), has a density of about 2.7 g per cm^3. The other materials probably range in density from less than 1 g per cm^3 for volcanic ash to 2.6 g per cm^3 for conglomerate. The deposits are composed dominantly of fine-grained materials that are more indurated and denser at depth and have an estimated average density of about 2.3 g per cm^3.

The magnetic susceptibilities of several samples of the igneous and sedimentary rocks were determined by means of a magnetometer and the field method described by Hyslop (1945, p. 242-246). The values obtained by this method are only approximate and are significant only as an indication of the possible range in susceptibility of the different rock types. Determinations made on samples of the flow rocks and tuffs of the Elkhorn Mountains Volcanics revealed susceptibilities ranging from .0004 to .003 cgs units and indicated the presence of a small amount of remanent magnetization. Measured susceptibilities of the intrusive rocks ranged from .0008 to .006 cgs units: andesitic and basaltic rocks, .0014 to .0032 cgs units; stocks of quartz monzonite and related rocks, .0008 to .002 cgs units; gabbroic rocks, .002 to .0024 cgs units; those of a few syenodiorite samples averaged about .0055 cgs units. Susceptibility measurements of samples of the sedimentary rocks indicated that these rocks have relatively low magnetic susceptibility and, for the purpose of this report, may be considered to be essentially non-magnetic.

GEOPHYSICS

Field methods

Gravity measurements were made at 214 stations--mainly bench marks and other points of known elevation established by the U. S. Geological Survey, U. S. Coast and Geodetic Survey, and U. S. Bureau of Reclamation. A Worden gravimeter with a scale constant of about 0.5 milligals per dial division was used; all the measurements were referred to a base station established at the Helena Airport by Woollard (1958, p. 533). The data were corrected for drift, elevation, latitude, and effects of terrain within 7.5 miles of each station. An elevation factor of 0.06 mgal per foot, based on an assumed density of 2.67 g per cm^3, was used in computing elevation and terrain corrections.

Aeromagnetic data were obtained in the area concurrently with an airborne radioactivity survey conducted on behalf of the U. S. Atomic Energy Commission in 1955. Total-intensity magnetic measurements were made with a continuously recording AN/ASQ-3A magnetometer installed in a DC-3 aircraft. East-west traverses about half a mile apart were flown approximately 500 feet above the ground. Topographic maps were used for guidance, and the flight path was recorded by a gyrostabilized 35-mm continuous-strip camera. The distance from aircraft to ground was measured with a continuously recording radar altimeter.

Gravity features

Prominent negative anomalies lie over the Cenozoic sedimentary deposits in Prickly Pear basin and Townsend Valley and are separated by a low-amplitude high over the Spokane Hills. A narrow gravity low of much smaller size and lower amplitude, but of structural importance, is indicated by undulations in the contours between the Elkhorn Mountains and the Spokane Hills. These features are superimposed on a regional gravity gradient of less than one mgal per mile, positive eastward, which has been determined from data obtained over the Boulder batholith and adjoining valleys.

The center of the negative anomaly in Prickly Pear basin lies only a few miles southeast of the west end of Lake Helena and almost directly east of the Scratch Gravel Hills. Gradients associated with the anomaly are comparatively low; the highest, which average about 8 mgals per mile, are on the north and northeast sides. Data obtained in the Helena quadrangle to the west (fig. 1) show that the gravity relief in the western part of the basin is correspondingly low and that the contours continue to close around the northwest end of the anomaly with a small decrease in gradient.

The negative gravity anomaly over Townsend Valley is centered between White Creek and Bilk Gulch on the eastern side of Lake Sewell and is an extension of a major gravity low that lies in adjoining quadrangles to the south (Kinoshita and others, in press). The anomaly conforms with the general shape of the valley and is bounded by gradients that are of much greater magnitude than those in Prickly Pear basin.

Interpretation of gravity data

Interpretations of the gravity anomalies were made mainly from two-dimensional analyses as described by Dobrin (1952, p. 96-99). Subsurface configurations that would produce the amplitude and general form of the anomalies were computed from profiles of maximum gravity relief along traverses normal to the axis of the anomalies. The following simplifying assumptions were made: (1) The density contrast between Cenozoic deposits and the more dense pre-Cenozoic sedimentary rocks and most igneous rocks is 0.4 g per cm^3, (2) the residual anomalies are produced entirely by the density contrast associated with bedrock relief, and (3) the anomalies and the inferred geologic features have an infinite extent normal to the profiles.

An analysis of the gradients and of a gravity profile crossing the center of the anomaly in Prickly Pear basin (fig. 2) suggests that the bedrock surface dips 5° to 40° to form an arcuate depression near the middle of the basin. This depression is bounded on the northeast by relatively steep bedrock slopes that decrease to the north and west and become comparatively gentle to the south and southwest. The steeper slopes probably represent a fault zone which, along the northeastern side of the depression, has a computed aggregate throw of about 4,000 feet. The bottom of the depression is interpreted to be about 1½ miles wide and to lie at a maximum depth of approximately 6,000 feet. A body of igneous rock that is inferred from a magnetic anomaly, but has no obvious gravity expression, lies in the northwest part of the depression. The lack of gravity expression of this body suggests that the igneous rock has about the same density as the bedrock and does not extend upward into the Cenozoic sedimentary deposits. The depression may be a downwarp or, possibly, a fault block tilted down to the northeast with displacement distributed in zones of step-faults that have formed moderately steep bedrock slopes in the northern part of the basin.

A study of the gravity gradients in the northern part of Townsend Valley indicates that the contacts between Cenozoic valley deposits and the pre-Cenozoic rocks dip steeply and probably are high-angle faults. The high gradient along the northeast side of the valley is interpreted as due to a steep fault zone that follows the edge of the Paleozoic and Precambrian beds to at least the latitude of Canyon Ferry and has a minimum throw of about 8,000 feet near the mouth of White Gulch (fig. 3). This fault zone apparently cuts a concealed body of igneous rock that is inferred from the magnetic data to lie in the southeast corner of the area. A gravity gradient of smaller magnitude occurs along the northeast side of the Spokane Hills. This feature probably is the expression of a southeastward trending broad fault zone that lies mostly beneath Lake Sewell. These inferred fault zones form a graben that is about 5 miles wide near White Gulch and narrows to less than a mile wide near Magpie Creek.

The gravity low between the Elkhorn Mountains and the Spokane Hills is attributed to a narrow northwestward-trending bedrock trough which probably terminates a few miles northwest of Placer. Analysis of the gradients indicates that the trough deepens southeastward; it has a comparatively steep northeast side and, near Placer, is about 2,500 feet deep (fig. 3). It appears to be separated from the Prickly Pear depression by a rise in the bedrock that is suggested by an increase in gravity values near Clasoil and, to the south, by bedrock protruding into the valley. The steep side is inferred from the gravity data to be a fault zone which lies beneath sedimentary deposits along the southwest side of the Spokane Hills and continues southeastward into the adjoining quadrangle. Bodies of igneous rock indicated by the magnetic data lie along parts of the trough.

Magnetic features

The magnetic pattern consists of: broad features that express low magnetic relief over most of the Cenozoic sedimentary deposits; high magnetic gradients along the northern edge of the Boulder batholith; and prominent anomalies over the Antelope Creek stock and the intrusive rocks in the Spokane Hills and along the front of the Big Belt Mountains. In addition, high-gradient anomalies occur over the Cenozoic sedimentary deposits in the northwestern part of the map area and between the Spokane Hills and the Elkhorn Mountains.

Interpretation of magnetic data

The magnetic data were interpreted from methods described by Pirson (1940) and Vacquier and others (1951). Sources of the anomalies were assumed to be magnetized by induction in the earth's field, and the effects resulting from remanent magnetization not in the direction of the field were considered negligible. Depths to the disturbing bodies were estimated from measurements of the horizontal extent of the steepest magnetic gradients. The contrasts in magnetic susceptibility used in the data analysis are based on susceptibility measurements of surface-rock samples and on estimates made from the anomaly amplitudes and assumed horizontal dimensions of the anomaly sources.

A prominent magnetic anomaly that is assumed to be associated with a mass of igneous rock occurs over Cenozoic sedimentary deposits in the northwest part of the area. Although this anomaly was not mapped completely by the aeromagnetic survey, ground magnetic measurements reveal that it is a narrow arcuate branch of a large anomaly that lies over the Scratch Gravel Hills to the west. The inferred igneous mass may be part of a syenodiorite intrusion exposed in the Scratch Gravel Hills, or it may be a body of diorite porphyry or gabbro such as that exposed along the northern and western borders of the Hills (Knopf, in press; Pardee and Schrader, 1933, p. 18, pl. 2).

Southeast of Lake Helena and extending south from near the Harmony School is a narrow anomaly that is probably caused by electrical power transmission lines. Other small anomalies that are attributed to power installations and industrial equipment lie over East Helena and eastward along the railroad.

The high magnetic gradients in the south-central part of the East Helena quadrangle are associated with gabbroic to granodioritic rocks in the northern part of the Boulder batholith. A study of these gradients and their magnetically low counterparts, which border the sedimentary-igneous rock contact, indicates that the concealed northern face of the batholith is nearly vertical. From geologic data (Smedes, 1962; Knopf, in press), the batholith contact there is known to be steep; commonly it is vertical, and locally it dips inward (to the south).

An analysis of the anomaly over the Antelope Creek Stock indicates that the northwest and northeast sides of the stock are steep and that the stock extends northeastward under valley deposits to within a mile of the railroad. The gradient on the northwest side of the anomaly correlates with a northeast-trending fault along Sheep Creek (Smedes, 1962). The conspicuous linear gradient on the northeast side suggests that a northwest-trending fault may lie along that side of the stock; but here the gravity data indicate comparatively gentle bedrock slopes. Geologic studies (Smedes, 1960) show that the intrusive contacts on the west (and south, beyond the map area) are steep, and suggest that the northwest and northeast parts are truncated by steep faults.

The positive magnetic anomaly in sec. 18, T. 9 N., R. 1 W. and another of comparable size about 1½ miles to the north are attributed to small steep-walled intrusive bodies that lie in the bedrock. That the upper part of these masses lie near the bedrock surface and are covered by not much more than a thousand feet of sedimentary deposits can be interpreted from the magnetic and gravity data. The southern body lies near the axis of an inferred southeastward-plunging syncline. If the inferred syncline afforded structural control for the emplacement of the intrusive rocks both bodies probably are postorogenic and satellites of the Boulder batholith. A larger body (porphyritic grandodiorite of Knopf, 1957, map, and in press) in similar structural position lies west of Helena.

The exposed monzonite stocks and dikes in the northern half of the Spokane Hills (Mertie and others, 1951, p. 44-50) give rise to magnetic maxima that are superimposed upon a broad elongate positive magnetic anomaly. The exposed igneous bodies probably are the roof parts and upward extensions of a large steep-walled stock, which is inferred from the large anomaly to lie several thousand feet beneath the surface throughout much of the northern part of the Spokane Hills and Lake Sewell. The northern gradient and bordering magnetic low of the anomaly suggest that this larger igneous mass terminates abruptly near Canyon Ferry. The exposed bodies of monzonitic and related rocks were considered by Mertie, Fischer, and Hobbs (1951, p. 45) to be genetically related to the Boulder batholith; probably the inferred stock and smaller igneous rock bodies marked by anomalies in the southern part of the Spokane Hills also are satellites of the Boulder batholith, which lies to the southwest.

Near the southeastern corner of the map is a prominent narrow magnetic anomaly that is associated with exposed monzonitic and lamprophyre intrusive bodies. Analysis of the anomaly indicates that these bodies dip steeply to the west and may be connected at depth. They lie in the Disturbed Belt (Robinson, 1959, p. 34) and are part of a zone of igneous rocks, inferred from magnetic and geologic data, extending in a crude arc through the Duck Creek Pass quadrangle to the south. The source of a low-gradient anomaly near the mouth of White Gulch seems to be a part of this zone, but it may be more deeply buried.

STRUCTURAL IMPLICATIONS

Results of the geophysical investigation supplement information obtained in geological studies of the region and give additional evidence indicating that Prickly Pear basin and the Townsend Valley are structural depressions. The gravity anomalies probably represent relief on the bedrock surface that is the result of Cenozoic block faulting and downwarping (Pardee, 1950, p. 366; Mertie and others, 1951, p. 55). The magnetic anomalies are interpreted to be the expressions of intrusive igneous rocks, some of which were emplaced before and some after a main period of orogeny.

The axes of the Prickly Pear depression and the trough between the Elkhorn Mountains and the Spokane Hills trend northwest and are in line with a small branch and the center of a large fault block or graben, which is inferred from gravity and geologic data (Kinoshita and others, in press) to underlie the central part of Townsend Valley to the southeast. The approximate coincidence in trend and alinement of these features suggests that they are parts of a single structural unit. However, the interpretation of gravity data indicates that the bottom elevation of the trough (fig. 3) is approximately 4,500 feet higher than that of the bedrock floors in Prickly Pear basin (fig. 2) and central Townsend Valley (Kinoshita and others, in press, fig. 1), which are inferred to lie more than 2,000 feet below sea level. This large difference in bottom elevations of the trough and the basins suggests that Prickly Pear basin and Townsend Valley may have been formed as separate structural features and that after their development in early Tertiary time drainage between the basins was blocked by a broad bedrock ridge. The basins, however, may have been formed as a structural unit and separated later by recurrent relative uplift that formed the ridge and the Spokane Hills (Freeman and others, 1958, p. 531-533; Mertie and others, 1951, p. 55-56).

The trough between the Elkhorn Mountains and the Spokane Hills very likely is a fault zone. It is nearly parallel to a set of steeply dipping normal faults in the Spokane Hills (Mertie and others, 1951, p. 53) and cuts the concealed northeastern limb of an anticline, which is exposed to the west in pre-Cenozoic sedimentary rocks along the front of the Elkhorn Mountains (Smedes, 1962). Geologic studies suggest that there may be considerable horizontal as well as vertical displacement across the trough and that the trough probably lies in a structural complex.

The broad north-trending ridge, which comprises the Spokane Hills, is partly bounded by inferred faults and is separated from the mountains to the north by a segment of the Disturbed Belt (Robinson, 1959, p. 34). Steep slopes that may be the result of faulting also lie along the west side of the ridge. This ridge probably is a horst, wedge-shaped in plan, that is underlain by a large pluton inferred from the magnetic data. The pluton lies outside the Disturbed Belt and is thought to be satellitic to the Boulder batholith.

The depression in the northern part of Townsend Valley may represent the northern branch of the Townsend Valley fault block (Kinoshita and others, in press). Its corresponding gravity anomaly is an extension of a broad gravity low that defines the main block in the central part of Townsend Valley to the south. Depth estimates indicate that the bottom of the depression is about 2,000 feet lower than that of the bedrock floor in the center of the valley. The concealed fault zone along the northeastern side continues southeastward and forms a part of the eastern side of the valley fault block. This fault zone was postulated by Mertie, Fischer and Hobbs (1951, p. 55) and by Nelson (1963). The inferred bedrock configuration and fault pattern are in complete accord with the following interpretation of the northern Townsend Valley basin, summarized from the report of Mertie, Fischer, and Hobbs (1951, p. 55-56): Townsend Valley was formed at the outset as a graben or block that dropped downward along two bounding faults with little or no tilting of the bedrock floor. The bounding faults cut across and clearly postdate folds and thrust faults of the Disturbed Belt formed during the Late Cretaceous (Laramide) orogeny, and intrusive rocks of Late Cretaceous or Paleocene age. Further movement along the northeast side of the graben occurred in late Oligocene time and resulted in east-northeasterly tilting of the older Oligocene strata. Similar tilting continued throughout most of Miocene time.

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