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BOUGUER GRAVITY, AEROMAGNETIC, AND GENERALIZED GEOLOGIC MAP OF THE EASTERN PART OF THE THREE FORKS BASIN, BROADWATER MADISON, AND GALLATIN COUNTIES, MONTANA

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Introduction

Gravity and aeromagnetic surveys were made in the Three Forks Basin, southwestern Montana, as part of a geologic study of intermontane basins along the upper Missouri River. The work was done primarily to detect concealed igneous rocks and to determine the configuration of the bedrock surface beneath Cenozoic continental sedimentary deposits that occupy the main valleys. This information was used in conjunction with the results of geologic mapping to interpret other concealed geologic features.

The Three Forks Basin is an irregularly shaped lowland that occupies about 1,000 square miles at the head of the Missouri River. It includes the valleys of the lower Gallatin, Madison, and Jefferson Rivers, which join to become the Missouri. Unlike most of the intermontane basins in Montana, which trend north-south, it is elongated east-west, being about 40 miles long and 25 miles wide. The basin is bounded by low hills on the north and by high mountain ranges on the east, south, and west.

The region shown on the map is that part of the basin and the bordering hills and mountains lying east of long 110°30' W. and south of lat 46°00' N. It includes the Manhattan, Belgrade, Anceney, and Bozeman 15-minute quadrangles and the western parts of the Sedan and Bozeman Pass 15-minute quadrangles; and comprises approximately 980 square miles in southern Broadwater, northeastern Madison, and central Gallatin Counties.

The basin area includes the Gallatin Valley, the lower part of Madison Valley, and the valley of Dry Creek, which projects northward from the eastern part of the basin proper. The master stream of the area, the Gallatin River, enters the south side of the basin through a long canyon and flows northwestward across it to join the Missouri River in the northwest corner. The Madison River skirts the west side of the area, and joins the Jefferson River to form the Missouri River a mile west of the mouth of the Gallatin River. The broad flood plains of the Gallatin and Madison Rivers, which lie at altitudes of 4,000 to 4,600 feet, are separated by the Camp Creek Hills. These hills are broad benchlands that rise steplike to altitudes of more than 5,000 feet. Scattered along the margins of the basin are similar but less continuous benches that reach altitudes of nearly 6,000 feet at the mountain fronts. The bordering mountains of the Bridger Range on the east and of the Gallatin and Madison Ranges on the south rise abruptly to crests of 6,500 to 10,000 feet. Ridges in the rolling Horseshoe Hills on the north are about 1,000 feet higher than the basin lowland.

General geology

The geology and hydrology of the eastern part of the basin itself are fairly well understood, mainly as a result of the work of Hackett and others (1960). The hilly northwestern and mountainous eastern borders of the basin have also been mapped in detail, recently, by Peter Verrall (1955) and McMannis (1955), respectively. The geology of the mountains to the south, however, is poorly known, mostly from reconnaissance studies by Peale (1893, 1896) and Clabaugh (1952). Consequently, the pre-Tertiary geology south of the basin is merely sketched on the accompanying map, and is confined to a mere fringe in some sectors.

The geologic discussion which follows is a series of crude vignettes of the local geology. The regional setting is discussed elsewhere (McMannis, 1955; Robinson, 1959, 1961, and 1963).

The foothills and mountains in the southern part of the area are underlain mostly by gneiss and schist of early Precambrian age. These rocks are involved in complex structures that trend northwestward (Clabaugh, 1952, p. 64). Narrow northwest-trending belts of folded Paleozoic and Mesozoic sedimentary rocks lie within the metamorphic rocks south and southwest of Gallatin Gateway. These belts are bounded on the northeast by steep faults. Another belt of deformed Paleozoic and Mesozoic strata underlies the foothills east and southeast of Boseman. The metamorphic and the sedimentary rocks are cut by small bodies of andesite porphyry, peridotite, and other igneous rocks (Claubaugh, 1952, p. 60). Andesitic volcanic rocks of probable late Eocene or early Oligocene age (Horberg, 1940, p. 283) underlie the upper slopes of much of the Gallatin Range.

The mountains of the Bridger Range are underlain by deformed Precambrian, Paleozoic, and Mesozoic rocks. As described by McMannis (1955, p. 1416), "The range, in general, consists of steeply dipping Paleozoic sediments trending arcuately from Bridger Canyon on the south to Blacktail Mountain on the north. The Paleozoic rocks are flanked on the west by a narrow strip of Precambrian metamorphics in the south half and by Precambrian arkoses in the north half; on the east they are bordered by less resistant, strongly upturned Mesozoic strata. Locally, on the west, the metamorphic rocks contain infolded and infaulted remnants of Cambrian and Devonian rocks. The west side of the Precambrian terrane is terminated by steep late Cenozoic faultline scarps. The structure of the northern half of the range is further complicated by a series of high-angle faults trending generally northwest, on which movement has been both by strike slip and dip slip. In the southern half of the range faults having a variety of trends and dips produce complex relationships."

The Horseshoe Hills on the northwestern flank of the basin are underlain by sedimentary rocks ranging in age from late Precambrian to Late Cretaceous. The strata throughout have been deformed into tight northeast-trending folds that are overturned to the southeast and are cut by several west-dipping thrust faults and a few steep faults all trending parallel to the folds.

Several sills are exposed in the hills. The most notable of these lie near Chipmunk Gulch west of Menard, near the head of Nixon Gulch, along Cottonwood Gulch, and in the southernmost fold of the hills.

The basin is underlain by Tertiary deposits, a few thousand feet thick, consisting of conglomerate, bentonitic sandy clay, siltstone, sandstone, and tuffaceous sandstone and siltstone (Hackett and others, 1960, p. 32-46). These deposits contain much rhyolitic and latitic ash and are covered by terrace and flood plain gravel, fan gravel, and windblown silt. Many of the deposits are poorly consolidated or unconsolidated. The more consolidated beds are tilted to form a homocline dipping 1° to 5° eastward toward the Bridger Range and terminating in a major fault zone at the mountain front (Pardee, 1950; McMannis, 1955). In Gallatin Valley, Hackett and others (1960, p. 50-53) observed several small normal faults, most of which are parallel to the Bridger frontal fault zone; and they mapped a monoclinal fold that trends eastward across the northern part of the valley. The general east-west elongation of the basin is believed due to a major concealed fault zone (Peale, 1896), called the Willow Creek fault (Robinson, 1961), that separates the dominantly sedimentary rocks to the north from the dominantly metamorphic rocks to the south.

The Precambrian rocks consist of medium-grade metamorphic rocks, mainly gneisses and schists, and sedimentary rocks that near the basin are mostly arkosic sandstones and conglomerates and siltstones. The Paleozoic and Mesozoic sedimentary rocks are mainly marine carbonate rocks, shale, and sandstone. Density determinations made from well-cemented surface samples of most of these rocks indicate that the densities of the metamorphic rocks range from 2.6 to 3.0 g per cm^3, with an average density of 2.8 g per cm^3, and that the densities of the sedimentary rocks range from 2.5 to 2.9 g per cm^3, and average about 2.7 g per cm^3. Measured densities of the igneous rocks in the region range from 2.6 per cm^3 for granite to 3.2 g per cm^3 for gabbro.

Densities were determined for only a few of the Cenozoic rocks. Measurements made on samples collected from the more resistant beds showed values of 2.2 g per cm^3 for tuff to 2.5 g per cm^3 for tuffaceous sandstone and grit. Limestone, present only locally as thin beds, has a density of about 2.6 g per cm^3. The other basin 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. These dominantly fine-grained and poorly consolidated deposits are assuredly more indurated and denser at depth. The estimated average density of the sedimentary deposits is about 2.3g per cm^3.

The magnetic susceptibilities of several samples of rocks in and near the area were determined by means of 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 probable range in susceptibility of the different rock types. The metamorphic rocks have susceptibilities ranging from up to 0.003 cgs units. The igneous rock samples showed a susceptibility range of 0.0008 to 0.006 cgs units; andesitic and basaltic rocks, 0.001 to 0.003 cgs units; stocks of quartz monzonite and related rocks, 0.0008 to 0.002 cgs units; gabbroic rocks, 0.002 to 0.003 cgs units; a few syenodiorite samples averaged about 0.005 cgs units. Measurements of samples of the sedimentary rocks indicate that these rocks have relatively low magnetic susceptibility and for the purpose of this report may be considered essentially nonmagnetic.

Geophysics

Field methods

Gravity measurements were made at 422 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, Montana, 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 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 gyro-stabilized 35-mm continuous-strip camera. The distance from aircraft to ground was measured with a continuously recording radar altimeter.

Gravity features

Prominent negative anomalies, that are parts of a major gravity low, lie over the Cenozoic sedimentary deposits along the base of the Gallatin Range and the southern part of the Bridger Range. Another negative anomaly, of smaller amplitude, occurs over the deposits between the Horseshoe Hills and the northern part of the Bridger Range. These anomalies are separated by the eastern ends of gravity highs whose maxima lie over metamorphic rocks in the Camp Creek Hills and over sedimentary rocks and deposits along the southern margin of the Horseshoe Hills. The main gravity low occupies much of the east part of the basin and is bounded in part by high gradients that are of maximum magnitude along the mountain fronts. Elsewhere the gravity features are flanked by moderately low uniform gradients.

Interpretation of gravity data

Interpretations of the gravity anomalies were made mainly from two-dimensional analyses as described by Dobrin (1952, p. 96-99). The following simplifying assumptions were made: (1) The density contrasts between Cenozoic deposits and the more dense pre-Cenozoic metamorphic rocks and sedimentary rocks are 0.5 and 0.4 g per cm^3, respectively; and (2) the local anomalies are produced entirely by the density contrast associated with bedrock relief.

An analysis of the gradients and of a gravity profile crossing the center of the southernmost negative anomaly indicates that a bedrock trough occurs beneath the southeastern margin of the basin. Near South Cottonwood Creek the bottom of the trough is computed to be about 2 miles wide and approximately 6,000 feet beneath the surface. Northeastward the trough broadens slightly, then narrows, and becomes shallower southeast of Bozeman. The subsidiary low in the eastern part of the anomaly coincides with a large alluvial fan and may be caused in part by the low density of the fan material. The high southeastern gradient of the main anomaly probably is the expression of a concealed steep fault zone that lies along the base of the Gallatin Range. The fault zone is inferred to extend northeastward from the mouth of Gallatin River canyon to Bear Creek and to have at least 4,000 feet of throw beneath South Cottonwood Creek. East of Gallatin Gateway the gravity gradients suggest that more than 2,000 feet of vertical displacement has occurred along another fault zone on the northwest side of the trough. This inferred fault zone lies between Yankee Creek and Middle Creek and may transect the frontal fault zone of the Gallatin Range. Northwest of the trough the bedrock surface rises gradually with minor undulations to the bedrock outcrops in the Camp Creek Hills.

Northward the gravity pattern indicates that the bedrock rises to form a broad low ridge between the trough and another deep depression in the bedrock near Belgrade. The ridge extends eastward from the metamorphic rock outcrops at Pine Butte to the metamorphic and sedimentary rocks exposed in the southern part of the Bridger Range. Near Bozeman the concealed eastern end of the ridge is marked by a narrow gravity high.

The gravity low centered east of Belgrade is interpreted to be the expression of an oval bedrock depression with a westward-trending arm, which shallows out gradually beneath the Camp Creek Hills south of Logan. The gravity gradients suggest that the main part of the depression is bounded by steep slopes on the east and north and by comparatively gentle slopes on the south and southwest. Its depth is estimated to be about 5,000 feet. The thickness of Tertiary deposits in this part of the basin seems therefore to be much greater than implied earlier (Robinson, 1961, p. 1009). The eastern side probably represents a fault zone that lies beneath Cenozoic deposits about 1½ miles west of their exposed contact with the metamorphic rocks at the base of the Bridger Range. This fault zone dips to the west and has an estimated aggregate throw of about 2,500 feet. It is regarded as a concealed part of the fault system that lies along the front of the Bridger Range.

The northern side of the depression very likely represents an eastward-trending fault zone that lies beneath Cenozoic deposits north of Belgrade. Interpretation of the gravity data indicates that this inferred fault zone dips southward and has at least 2,000 feet of vertical displacement. Beneath the eastern margin of the basin the fault zone probably transects west-northwestward-trending faults exposed in the front of the Bridger Range. West of the Gallatin River the gravity expression of the fault zone dies out and the gravity gradients suggest that bedrock likes at comparatively shallow depths throughout the northern part of the Camp Creek Hills and the Madison River valley. The fault zone may be a part of the Willow Creek fault zone that was active in Cenozoic time.

Northward the gravity pattern is interpreted as indicating that the bedrock again rises to form a low east-trending ridge, which lies between the depression centered near Belgrade and the southern end of a small bedrock hollow underlying Dry Creek valley in the northeast corner of the area. The ridge underlies the southern border of the Horseshoe Hills and extends eastward from Logan to the front of the Bridger Range. This ridge may represent an east-plunging anticline in the basement whose eastern end also has been truncated by faults and is exposed in the mountain front. The gravity high near Logan may be the expression of the highest part of the fold. There the crystalline rocks are interpreted to lie at a depth of less than 1,000 feet.

The gravity low in the northeast part of the area is interpreted to be the southern part of a depression in which Tertiary sedimentary rocks are preserved beneath Quaternary deposits between the Horseshoe Hills and the Bridger Range. Although faults are known to occur along the margin of the Horseshoe Hills south of Menard and along the base of the Bridger Range, there is no pronounced gravity evidence of faults within the depression. The gradients of the anomaly are of low magnitude and indicate that the pre-Tertiary bedrock surface slopes gently downward toward the middle of the depression, which probably is not more than 3,000 feet deep.

Magnetic features

A zone of high-gradient magnetic anomalies extends east and northeast from the Camp Creek Hills to the Bridger Range. This zone lies over metamorphic rocks exposed in the central part of the hills and over the broad expanse of basin deposits between the Madison Plateau and the front of the Bridger Range. A northeastward-trending belt of narrow anomalies marks intrusive bodies in the central and eastern parts of the Horseshoe Hills. Small anomalies that are probably due to industrial sources occur over Bozeman and along railroads in the Missouri River canyon in the northwest part of the area. Only minor variations in magnetic intensity are present in the remaining parts of the area.

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.

The magnetic pattern over the metamorphic rocks exposed in the Camp Creek Hills and in the foothills of mountains in the adjoining quadrangles to the west is characterized by many small discontinuous high-gradient anomalies whose sources very likely lie near the surface and may crop out in places. These anomalies are probably caused by local variations in magnetic susceptibility within the basement complex and by small intrusive bodies that have invaded the metamorphic rocks.

The continuation of this anomalous zone east of the Madison River and the presence of metamorphic rock outcrops in the Camp Creek Hills and along the fronts of the Gallatin and Bridger Ranges suggest that the basement rocks underlie the Cenozoic deposits throughout much of the eastern part of Three Forks Basin. A prominent magnetic gradient along the northern side of the anomalous zone probably marks the concealed contact between the basement rocks and the pre-Cenozoic sedimentary rocks that underlie deposits in the northern part of the basin. The inferred contact trends northeastward from near the Upper Madison School to about the latitude of Central Park and then swings to the east. Beyond the East Gallatin River, the magnetic expression of the contact is masked by thick Cenozoic deposits. However, a low-gradient anomaly near Reese Creek indicates that the basement rocks continue eastward to join the metamorphic rocks exposed in the mountain front northeast of Springhill School. This anomaly and gradients to the west correspond with the position of an eastward-trending fault zone inferred from the gravity data.

In the western part of the zone are several northeastward-trending anomalies that may be associated with intrusive bodies in the metamorphic rocks. The most prominent of these lie in a belt that trends northeastward through Vincent. These narrow anomalies are especially suggestive of deformed sheetlike masses of intrusive rocks; they may, however, be the expression of steeply dipping lenses of amphibolite or other iron-rich metamorphic rocks.

In the southern part of the anomalous zone small ridges on the metamorphic rock surface cause low-amplitude anomalies near Pine Butte and southeast of Anceney. Over Yellow Dog Creek, about a mile southwest of the Pine Butte School, is a high-gradient anomaly that may be due to an oval-shaped intrusive body that lies near the surface. The prominent 160-gamma anomaly west of Bozeman is probably associated with a comparatively large intrusive body. The top of this mass lies at an estimated depth of about 3,000 feet, which, inferred from gravity data, corresponds to that of the metamorphic bedrock surface.

Along the margin of the basin east of Bozeman are small positive and negative anomalies that appear to be associated with fault zones in the pre-Cenozoic sedimentary rocks. These anomalies may be caused by magnetic susceptibility contrasts in the basement rocks which lie at shallow depths on the upthrown side of the faults. Some of the anomalies, however, may be associated with concealed intrusive bodies in or near the fault zones. North of Bozeman, the presence of metamorphic rocks beneath the Cenozoic deposits is indicated by small variations in magnetic intensity. To the north, near Belgrade, the magnetic expression of these basement rocks is masked by Cenozoic deposits in the deeper part of the basin.

Narrow northeastward-trending anomalies mark sills in the tightly folded pre-Cenozoic sedimentary rocks of the Horseshoe Hills. The comparatively weak magnetic expression of the sill in the southernmost exposed fold is probably due to the near correspondence between the trend of the sill and the direction of the flight lines. This sill, or similar ones in the same zone, continues southwestward beneath the Cenozoic deposits for more than 2 miles. Sills in the fold near the mouth of Cottonwood Gulch also continue into the basin. Their southern extremities, though not prominently defined by the magnetic data, probably lie beneath basin deposits more than a mile south of the railroads west of Logan.

Other structural implications

Interpretation of the geophysical data reveals that the bedrock surface within the eastern part of the basin is irregular and is comprised mostly of features that appear to be structural rather than erosional. Eastward tilting of the basin, beginning in late Eocene time and recurring during the rest of the Tertiary Period, has been suggested (McMannis, 1955, p. 1426-1427; Robinson, 1961, p. 1009) to account for the attitude of Tertiary beds and their overlap on older rocks. Evidence of such tilting in the bedrock may be inferred from the thickening of basin deposits toward the Bridger and Gallatin Ranges. Several broad folds of diverse trend have been observed in the Eocene and Oligocene rocks in the western part of the basin (Robinson, 1961, p. 1009-1010, and 1963, p. 113) but only one has been detected in the Miocene and Pliocene rocks that crop out in the eastern part (Hackett and others, 1960, p. 51-53). The inferred bedrock ridges may represent pre-Miocene folding along east-west axes in the older Tertiary rocks beneath the little deformed cover.

The eastern ends of the folds have been truncated by faulting in a zone near the base of the Bridger Range along which the basin has sunk and the range has risen since Oligocene time (Pardee, 1950, p. 380, and McMannis, 1955, p. 1426-1427). Eastward tilting of the bedrock doubtless accompanied this faulting, which also has formed the eastern side of the bedrock depression near Belgrade. Cenozoic movement along inferred faults near the base of the Gallatin Range probably formed the narrow buried trough in the southeastern margin of the basin.

Southwest of Logan the gravity data indicate a bedrock saddle that trends southwestward from the Horseshoe Hills. This feature seems to be the hidden continuation of the Laramide deformed belt of sedimentary rocks exposed in the hills, which is considered to be a part of the Sixteenmile thrust zone (Robinson, 1959; 1963, p. 105-106).

The inferred fault zone along the northern side of the depression near Belgrade probably is the contact between sedimentary rocks of the Belt Series and the metamorphic rocks; it may be a segment of the Willow Creek fault and be related to the Pass fault zone in the Bridger Range (McMannis, 1955, p. 1420-1421, 1425). McMannis found that the Pass fault zone marks the southern extent of Belt rocks and the northern limit of the Precambrian metamorphic rocks in the Bridger Range, and surmised that movement along this fault during Precambrian time, south side up, controlled deposition of the Belt rocks, as first recognized by Peale (1893, p. 14). Much later, reversed movement along the fault, and folding in the stratified rocks, elevated the rocks on the north side so that now the south side is relatively down. A similar interpretation has been suggested for the Willow Creek fault (Robinson, 1963, p. 102-107).

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