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Regional Gravity Survey of Western and Central Montana[1]

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Abstract A regional gravity survey of western and central Montana comprising data from more than 2,700 gravity stations was interpreted by automated computer techniques, including use of least-square polynomial surfaces as approximations to the regional gravity field.

The Bouguer gravity anomaly map of western and central Montana shows a large northwest-trending gravity low of −175 mgal across the fold-and-thrust belt of the Montana Rockies and two northwest-trending zones of gravity contours that increase sharply eastward. One of the zones is in the Lewis thrust area and the other is east of the Disturbed Belt. An increase in the Bouguer gravity anomalies continues eastward from the Montana Rockies to the Great Plains of eastern Montana, where gravity values of more than −55 mgal are found.

Two prominent northeast-trending residual gravity anomalies of +20 mgal in the western Montana plains probably reflect igneous ridges at the top of the basement. Northeast-trending residual anomalies of +20 mgal are associated with the Bearpaw arch; they are believed to be reflections of large near-surface intrusive bodies, perhaps cupola features of a deep-seated parent body. Distinctive positive residual anomalies over the Big Snowy and Women's Pocket uplifts and over the Porcupine and Bowdoin domes are attributed to uplifted crustal blocks that produced arching in the sedimentary sequence. Several significant negative residual anomalies are believed to be expressions of structural basins between positive features. The general northeast trend of the regional gravity anomalies of western and central Montana suggests a genetic relation with the pre-Paleozoic structural grain of southern Canada and the north-central United States.

Introduction

During the summer and fall of 1963, a U.S. Air Force gravity survey team, under my direction and supervision, conducted an extensive gravity survey in western and central Montana (Fig. 1). The survey of more than 2,700 gravity stations, from approximately lat. 45°N to 49°N and from long. 106°W to 115°W, was conducted as a geodetic feasibility study. After initial data reductions by the U.S. Air Force, the data were released to me. An additional 1,100 stations were observed subsequently in areas of northwestern Montana by U.S. Air Force gravity survey teams and by members of the Regional Geophysics Branch, U.S. Geological Survey. More than 3,800 gravity stations were covered, about 2,700 of which are included in the Bouguer and residual gravity anomaly maps (Figs. 2, 3).

Consideration of the regional gravity field of an area as large as that considered herein i effective means of determining large-scale surface geologic structure. A regional gr analysis requires relatively less dense st spacing and less restricted data control does a detailed survey. Areas of irregular tion distribution, lack of stations in inacce areas, and limits on the overall accuracy o gravity data precluded detailed interpreta

The interpretation of regional gravity requires that the gravity anomalies gen considered to be associated with the smo large-scale basement and deep-crustal de inhomogeneities be separated from the nounced anomalies associated with near-su localized density contrasts. Thus, the re gravity anomaly to be interpreted can be sidered a filtered output of a high- or low filter that corresponds respectively to a lo regional feature. In my study, nonortho least-square polynomial surfaces were us filter operators to determine the residual g anomalies.

The principal objectives of my study gravity field of western and central Mo were (1) to present Bouguer and residual ity anomaly maps of the area (Figs. 2, 3 (2) to present a structural synthesis of tectonic features based principally on g

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W. E. Bonini and I will incorporate all of including the Bouguer gravity anomaly map, gional Bouguer gravity anomaly map of which will be available in 1970.

AREA MTwest Grav

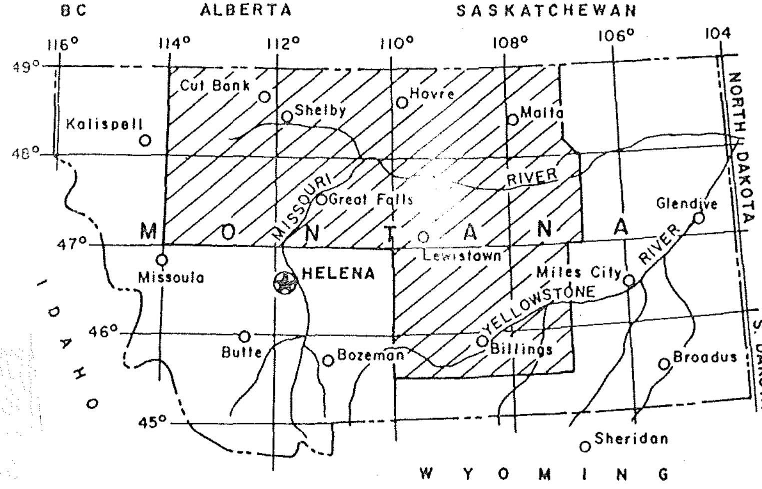

FIG. 1.—Index map of area covered by gravity survey of western and central Montana.

l geologic information. The Bouguer and re- l gravity anomaly maps presented are con- sed versions of maps produced originally at ale of 1:500,000, which corresponds to the e of the "Geologic Map of Montana."

Significant gravity anomalies of western and ral Montana were found in association with following geologic features: (1) the Mon- Rockies and associated Disturbed Belt, a central zone of domes and monoclinal ures, and (3) several major igneous fea- . In addition, large gravity anomalies, ap- ntly associated with basement structures, identified in the western Montana plains.

ious and Current Geophysical Studies

Gravity data for Montana first were pub- d by Woollard (1958) and Behrendt and llard (1961), who worked on the gravity rol network of North America. More re- information on the U.S. Gravity Network ollard and Rose, 1963) includes a general- Bouguer gravity anomaly map of the state. ce 1955, W. E. Bonini and his students been carrying out extensive reconnais- and detailed gravity surveys throughout of Montana. The results of several of surveys have been discussed in unpub- B.A. theses (Princeton University). Gravity interpretations for the Helena area presented by Renick (1965). Burfeind) discussed geophysical results from the lder batholith. Biehler and Bonini (in) also are working on a geophysical inter- ion of the Boulder batholith, which includes an interpretation of anomalies associated with the batholithic intrusion, and a review of past and current information on the origin, structure, and emplacement of batholithic bodies.

Under the direction of G. W. Crosby of the University of Montana, gravity mapping throughout western Montana, including an underwater gravity survey of Flathead Lake, has progressed during recent years (Crosby, 1968, personal commun.). Gravity data for the Bitterroot Valley of southwestern Montana are being compiled by members of the Hawaii Institute of Geophysics, which also is conducting a study of gravity observations along a series of north-trending profiles across the western United States, including lines in Montana (Lawrence Machesky, 1967, personal commun.).

Mudge *et al.* (1968) reported gravity, aeromagnetic, and geologic information for economic and tectonic features of the southeastern part of the Lewis and Clark Range of western Montana. Part of the gravity data in their report are U.S. Air Force data that also are included here. Additional gravity data obtained by the U.S. Geological Survey have been compiled for the Bearpaw Mountains of central Montana, the Lewis and Clark Range of western Montana, and the Boulder batholith area of southwestern Montana (Mabey, 1967, personal commun.).

Aeromagnetic and gravity data have been interpreted for parts of eastern Montana (Zietz and Hearn, 1969), and large-scale aeromagnetic coverage for most of the Bearpaw Moun-

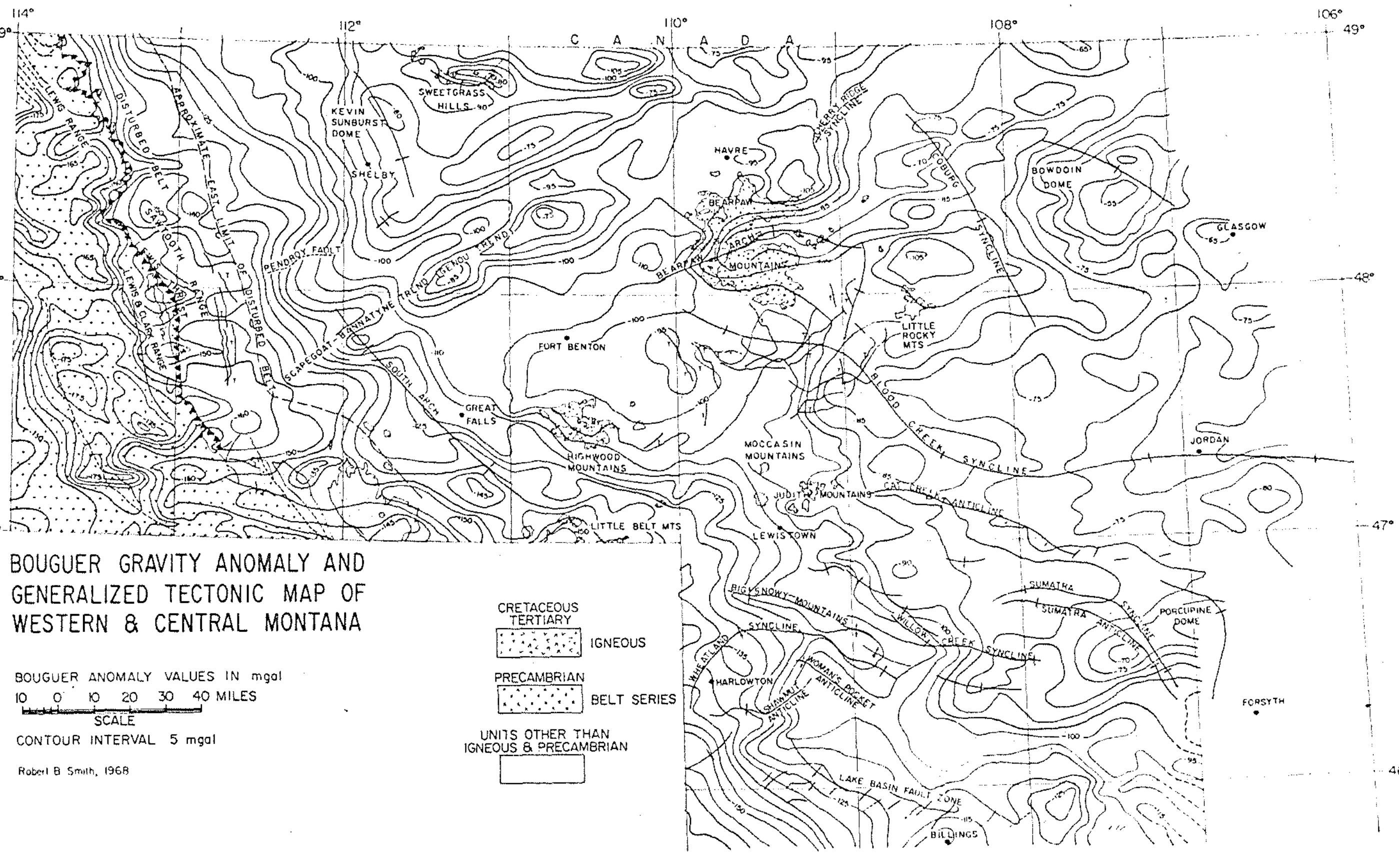

FIG. 2.—Bouguer gravity anomaly map of western and central Montana drawn on generalized tectonic base map. Tectonic base map after Dobbin and Erdmann (1955).

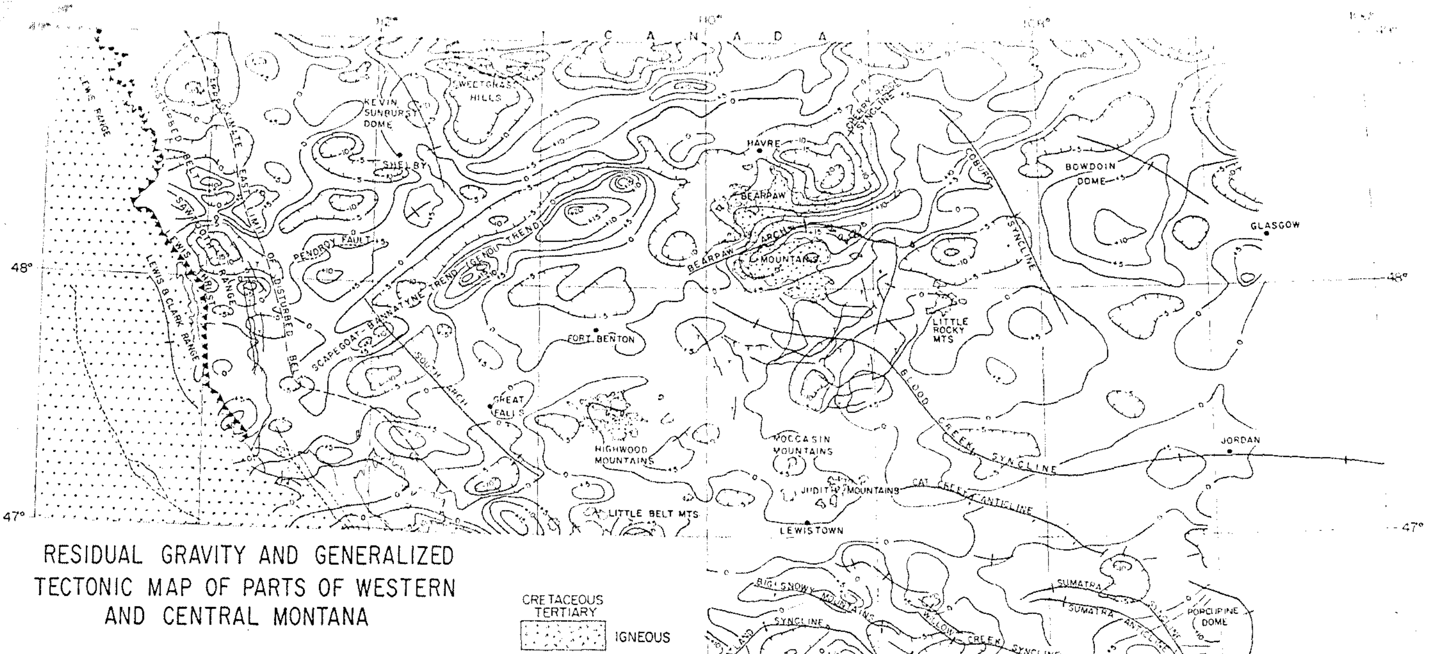

FIG. 3.—Residual gravity anomaly map of western and central Montana drawn on generalized tectonic base map.

tains has been released by the U.S. Geological Survey. The Bearpaw Mountains survey did not cover a large enough area to warrant integration with this study for a regional interpretation. Aeromagnetic data for parts of the Montana Rockies were released in open file by the U.S. Geological Survey in 1968, and both gravity and magnetic data for this area are being interpreted by members of the U.S. Geological Survey and by me. Limited open-file gravity data of the U.S. Geological Survey were used for part of the Lewis and Clark Range.

Field Methods

In 1963, more than 2,700 gravity stations and an associated base station network were established in western and central Montana. The main field program was conducted by a U.S. Air Force gravity survey team in support of a deflection of the vertical (gravity) feasibility test program. I directed and supervised field operations as a Geodetic Officer and Party Chief. As an additional support project, a survey of lesser extent was completed in northwestern Montana by the U.S. Air Force in 1965; 387 gravity stations were established to provide additional data for the base station network.

The 1963 field party consisted of four two-man field teams. The gravity meters used for the main survey were the Worden Master gravity meters 615, 616, 617, 682, and 691 and the LaCoste and Romberg geodetic gravity meters 43, 44, 47, and 48. Horizontal and vertical controls were obtained principally from topographic maps and established level lines. Where vertical control was unavailable, barometric altimeters were used.

Because of the requirements of the deflection of the vertical study, the gravity stations were selected with respect to their general location and distance to the deflection sites. Thus, gravity coverage was normally irregular in station spacing. Gravity loops were tied to an established base station network; maximum base station loop ties for normal field operations did not exceed 8 hours.

Data Reduction

Gravity reduction.—Standard gravity-reduction techniques were used to reduce the observed gravity data to a datum of mean sea level. A standard crustal density of 2.67 g/cc was used. The gravity-reduction methods were programmed and all data were computer-processed.

Wh... necessary, terrain corrections by use of the Hayford-Bowie charts were made ... stations in the Lewis and Clark Range, ... Lewis Range, the Sawtooth Range, the Hi... wood Mountains, the Sweetgrass Hills, the ... dith-Moccasin Mountains, and the Big Sno... Range. Terrain corrections for an area of ... treme topographic relief in the Lewis and Cl... Range of western Montana averaged 6 m... and ranged up to 21 mgal.

Mapping and analysis methods.—Gra... data were located by field teams on the lar... scale topographic maps available. Appr... mately 65 percent of the station elevations w... established by means of bench marks, level... elevations, and spot elevations from the to... graphic maps. The other station elevations w... obtained from barometric altimetry.

To facilitate station plotting and contou... of the data, a series of digital computer p... grams that included basic gravity reduc... station-location plotting, polynomial surfac... ting, gravity residual determination, mass-... eling techniques, and general machine con... ing was utilized.

The technique of least-square polyno... surface fitting was used as an approximatio... the regional gravity field where the differ... of the Bouguer gravity anomaly map from ... regional or computed surface was used for ... residual gravity anomaly map. A brief des... tion of the method has been given by C... (1966).

Accuracy of data.—The accuracy of th... gional gravity anomalies is influenced prim... by errors in station elevations, the exclusi... terrain effects, the uncertainty in the sel... and use of rock densities in reduction and ... eling techniques, and the improper selecti... limits and parameters used to describe mo...

Although elevation requirements were ... restrictive away from the central area of ... tigation, field teams attempted to mainta... strictest elevation requirements possible ... areas. Most elevations determined by alti... are believed to be accurate within 10 ft for ... of low to moderate topography and ... 30 ft for most stations in areas of mount... topography. Elevations determined at ... marks probably are accurate to 1 ft; spot ... tions probably are accurate within 3 ft. ... zontal positions for the general area ... lieved to be within 0.1 minute for 80 per... the stations; all of the stations are withi... minute.

The probable accuracy of the gravity ... for the complete survey is considered ...thin 0.2 mgal for base stations and within 0.3 ...gal for general station values. Actual comparisons of gravity readings taken in the 1965 survey at gravity bases were within a standard error of 0.2 mgal with respect to the gravity base network.

Base station network.—During the initial ...ages of the survey, a gravity base station network[1] was established that consisted of 67 stations at prominent and easily accessible locations throughout the survey area. Minimum base station requirements were two measurements of the gravity interval and agreement within 0.3 mgal. Initially, the field teams tied to Woollard's (1958) airport stations for relative gravity values. During the later computations ...d base net adjustments, all base stations were ...defined and converted to the Great Falls M... ...tum, which has an observed gravity value of ...0,532.71 mgal.

...uguer Gravity Anomaly Map of ...estern and Central Montana

Figure 2 is the regional Bouguer gravity ...omaly map of western and central Montana, ...own on a generalized tectonic base map. The ...gional gravity patterns reflect mainly density ...homogeneities in the earth's crust. The large ...ar-surface density contrasts in the Montana ...ckies are the result of Laramide uplift and ...rusting of Precambrian and Paleozoic rocks ... and over the surrounding Paleozoic and ...esozoic sedimentary rocks. Two Precambrian ...eous ridges at the top of the basement in the ...stern Montana plains are responsible for ...rtheast-trending positive gravity anomalies. ...mal and monoclinal flexing in central Mon...a has emplaced older and denser material in ...ntact with upturned Paleozoic and Mesozoic ...s; these relations are reflected by large posi... gravity anomalies. Several near-surface ...amide intrusions are reflected as smaller ...tive gravity anomalies.

A prominent feature of the Bouguer map is a ...rthwest-trending gravity low that corre...nds to the fold-and-thrust belt of the Mon... Rockies. This anomaly has a minimum of ...175 mgal over the mountain axis, and it coin... generally with the west flank of a large ...thwest-trending syncline in the Belt Series ...ecambrian) of the Lewis and Clark Range. ... regional Bouguer anomalies associated ... the Montana Rockies are more complex than those in the Gr...at Plains area on the east. In particular, they reflect density contrasts in the near-surface ...imentary beds and in the deeper crustal la.... The eastward increase in the Bouguer gr... anomalies associated with the Montana R...es represents decreases in thicknesses of th... ...ar-surface beds and density contrasts associat... with the Lewis thrust and the Disturbed Belt.

East of the Montana Rockies is an area of closely spaced gravity contours that corresponds to the transition zone between the Montana Rockies and the northern Great Plains. The eastward increase of the Bouguer anomalies from −150 to −110 mgal probably represents an isostatic transition region of the upper crust between the mountain region on the west and the plains on the east. Gravity models of this feature suggest two crustal models: (1) the introduction of a high-density layer into the upper crust at the east side of the Disturbed Belt that continues eastward through the Montana plains or (2) a marked eastward decrease in the depths of the upper crustal layers. The results of the modeling were not definitive, but the eastern limit of the abruptly changing gravity contours (up to 70 km east of the mountain front) and the model solutions suggest that the isostatic effects of the Montana Rockies are associated with significant structural changes in the crust that affect areas larger than those represented at the surface by known tectonic features.

Prominent gravity highs trend northeast in the northwestern Montana plains where two large positive anomalies are located transverse to the Sweetgrass arch. The anomaly associated with the Scapegoat-Bannatyne trend has a maximum regional value of −75 mgal and the northern feature, which begins in the Pendroy fault zone area and parallels the Scapegoat-Bannatyne trend, also is associated with a −75 mgal regional high. These large regional trends probably are associated with igneous basement features.

The gravity anomalies in the Great Falls area reflect gentle structural features of the western Montana plains and the igneous and domal tectonic features associated with the Highwood and Little Belt Mountains. In the northern Montana plains, igneous masses and associated uplifts are shown in the Bearpaw Mountains by Bouguer gravity anomalies of −80 mgal. The Bowdoin dome is represented by a closure of the regional Bouguer anomaly map, and is associated with a domal uplift of Laramide origin.

[1] Copies of the base station descriptions and as...d gravity values are available from the writer.

Gravity anomalies associated with the structural elements of the Central Montana platform are found in the Lewistown and Roundup areas. The general features of this region are represented by a group of local gravity highs and lows, and by an east-trending regional gravity anomaly distribution that ranges from −140 mgal west of the Big Snowy Range to −70 mgal on the Porcupine dome.

Regional gravity anomalies associated with the Lake Basin fault zone were not detected. This result probably is related to the lack of density contrasts between the fault blocks, and suggests that little vertical displacement has occurred. The gravity data suggest that the Lake Basin fault zone consists of horizontal displacements in the sedimentary sequence that could have been produced along a basement fault system.

A regional Bouguer profile extending from the northeastern part of the Montana Rockies (near Kalispell) eastward for 540 km into the northern Great Plains (Fort Peck Reservoir) was studied for information on crustal structure. Modified seismic models were used as control for gravity modeling. Interpretation of the profile indicates that the seismic and gravity data are compatible for two models that represent eastward dip along the Mohorovičić discontinuity and for a third model that requires westward dip. Interpreted crustal thicknesses are 40–56 km on the west and 50–58 km on the east.

Interpretation of Residual Gravity Anomalies of Western Montana Plains

As an aid in interpreting the regional geology and basement structure, the Bouguer gravity anomaly map of western and central Montana from lat. 46°N to 49°N and from long. 107°W to approximately 113°W was analyzed by the least-square polynomial method. The result is shown in Figure 3, an eighth-degree composite residual gravity anomaly map, which outlines additional detail that is not apparent on the Bouguer gravity anomaly map.

An interpretation of the geologic structures of the western Montana plains is considered here. The area covered is from lat. 47°N to 49°N and from long. 110°W to approximately 113°W. Two large parallel gravity highs that trend northeast across the Sweetgrass arch in the Shelby area are prominent in the western Montana plains. The southeastern feature coincides with the Scapegoat-Bannatyne trend. The Scapegoat-Bannatyne gravity anomaly is composed by three positive gravity highs that have maximum residual values of +20 mgal. This large feature, which extends northeastward as a major trend of gravity highs for ... mi, has a maximum width of 20 mi and is asymmetric. The steep flank is on the northwest, where gravity gradients of up to 5 mgal/mi are found.

A major feature northwest of the Scapegoat-Bannatyne anomaly, characterized by the alignment of three positive gravity highs, begins near the Pendroy fault zone and extends ... mi northeast toward Alberta. The maximum amplitude of residual anomalies associated with this feature is +15 mgal and the steeper gravity gradients are on the southeastern flank. Because of the apparent relation of the northern gravity anomaly to the Pendroy fault zone, the anomaly is designated the Pendroy gravity anomaly.

Geologic evidence of the Scapegoat-Bannatyne trend was published first by Alpha (1955, p. 132–133) who constructed structural contour maps, using as datum the base of the Cretaceous Colorado Shale in the Bannatyne field area of western Montana. In addition, a small structural high known as the Genou ... has been defined on the northeast end of the Scapegoat-Bannatyne trend.

Little has been written about either of the two trends, and Alpha's study (1955, p. 135) apparently is the only detailed report on the geology. According to him, the geologic evidence for the existence of the Scapegoat-Bannatyne trend is a series of structural anomalies which is expressed as a transverse fault zone in the Scapegoat Mountain area and, along the trend, becomes an alignment of structural highs which terminates with the Genou trend. This feature parallels the pre- and early Paleozoic structural trends of central and south-central Montana, the southern Canadian shield, and the north-central United States. Similar trends also are present in Montana in the Bearpaw arch, the east-trending faults and flexures of the Central Montana platform, the northeast-trending transverse igneous belt of central Montana, and the Pendroy fault zone. In addition, the geophysical evidence (Kanasewich, 1968) ... northeast- to east-trending Precambrian ... parallel with the Scapegoat-Bannatyne and Pendroy anomalies, 125 mi farther north in British Columbia and Alberta. Evidence of the major structure includes magnetic and gravity anomalies extending from northern Idaho northeastward approximately 300 mi into southern Alberta.

Alpha (1955, p. 133) reported that the basement on the Genou segment of the Scapegoat-Bannatyne trend may be as shallow as 3,000 ft below the surface. Drilling along trend indicates that the basement rocks are porphyritic andesite and trachyandesite. Alpha noted that the weathered character of the igneous rocks, the lack of metamorphism in overlying Cambrian and Devonian rocks in contact with basement rocks, and the overlap of the Cambrian suggest a Precambrian age for the earliest development of the Genou part of the Scapegoat-Bannatyne trend.

Data suggest, therefore, that the Genou trend is related to igneous activity that began during the Precambrian and produced erosional relief before the Paleozoic deposition. The geographic, structural, and geophysical relations of the Scapegoat-Bannatyne anomaly, compared with those of the Pendroy anomaly, suggest strongly a similar origin for the northern feature.

The distinct linear alignment of the two anomalies with the associated large gravity gradients suggests the presence of a well-defined anomalous body that has a large density contrast—as great as +0.4 g/cc—with the andesitic and sedimentary rocks. The parallelism between these two structural trends and the transverse igneous belt of central Montana suggests a genetic relation. The andesitic material may have been intruded along preexisting northeast-trending zones of weakness where it formed linear dikes and, perhaps, a limited type of laccolithic doming at the top of the basement. Subsidiary faulting, produced by the intrusion, probably occurred in a complex basement zone and is represented by the Pendroy fault zone at the surface.

Other small tectonic elements along the Pendroy anomaly that attest to the presence of an anomalous feature are the northeast-trending structures related to the Pondera and Conrad oil fields and a small northeast-trending anticlinal feature just south of the Kevin-Sunburst dome. These structural features and the Laramide structural relations of the Scapegoat-Bannatyne trend suggest that continued activity occurred along the Scapegoat-Bannatyne and Pendroy trends during Laramide deformation and that there was limited intrusion and uplift.

Between and parallel with the Scapegoat-Bannatyne and Pendroy anomalies is a large negative anomaly with maximum residual gravity values of −10 mgal. This anomaly appears near the southwestern end of the Pendroy anomaly and extends northeast to the end of the Scapegoat-Bannatyne anomaly. Probably this anomaly was produced by relative downwarp or by a downfaulted block between the two structural highs.

The Kevin-Sunburst dome, a north-northwest-trending gravity high, is a pronounced feature of more than +10 mgal on the residual gravity anomaly map. Evidence for the presence of the Kevin-Sunburst dome southward across the Pendroy and Scapegoat-Bannatyne trends is masked by the larger northeast-trending anomalies. However, if the axis of the Kevin-Sunburst anomaly is projected southeast, it coincides with positive peaks of the Pendroy and Scapegoat-Bannatyne anomalies. Thus, the residual anomalies over the larger northeast-trending features may be composite anomalies produced by the effects of both the north-northwest-trending and the northeast-trending features.

There is no gravity evidence for the South arch. However, a small north-northwest-trending positive residual anomaly just north of Great Falls may be indicative of the presence of a small structure related to the major feature. This anomaly has a residual high of approximately +5 mgal, but it is much smaller in areal extent than the Kevin-Sunburst dome.

The igneous and domal features of the Highwood Mountains do not produce a significant gravity anomaly. A gentle east-trending gravity high centered near the Highwood Mountains is evident on a second-degree residual map (not included here) of the western Montana plains. Probably the broad regional anomaly associated with the Highwood Mountains igneous features is related to a gentle basement uplift. Limited station distribution in the Highwood Mountains precluded a detailed gravity investigation of the area.

A northeast-trending zone of negative residual anomalies is present south of the Scapegoat-Bannatyne anomaly. This zone begins northwest of Great Falls and extends northeast for approximately 120 mi to its termination northwest of the Bearpaw arch. The average residual anomaly is approximately −5 mgal and maximum residual values of −10 mgal are found just west of the Bearpaw arch and northwest of Great Falls. Comparison with the

"Structure Contour Map of the Montana Plains" (Dobbin and Erdmann, 1955) shows the negative trend to coincide approximately with a broad northeast-trending structural depression. It is suggested that the negative trend is the result of basement downwarping and subsequent deposition, and that there may have been basement faulting along the south edge of the Scapegoat-Bannatyne trend and along the northwest boundary of the Bearpaw arch.

Interpretation of Residual Gravity Anomalies of Central Montana

The residual gravity anomalies of the area from lat. 45°45′N to 49°00′N and from long. 106°45′W to 110°00′W are not as pronounced as those associated with the basement trends in the western Montana plains. The main residual anomalies are primarily the result of anomalous bodies associated with uplifts, domes, and intrusive igneous centers.

The tectonic features of central Montana were developed in the general area of two major east-trending sedimentary troughs—a Proterozoic east-trending branch of the Belt trough and an east-trending basin of deposition developed during the Mississippian. The coincidence of the present major tectonic features in the same area suggests a correlation with deep-seated basement structures that have grown intermittently from the Proterozoic through at least the Laramide orogeny.

The large domal uplifts of Laramide age in central Montana were postulated by Eardley (1962, p. 566) to be the result of primary vertical uplift over deep-seated igneous features. Gravity sliding of surficial material is a secondary result. Eardley believed that the uplifts are the result of vertical movement that was produced by intrusions of large laccoliths in the granitic layer of the crust. The parent magma is thought to have been olivine basalt which, while still molten, assimilated parts of the crystalline granitic basement to form a secondary magma that was intruded into the overlying crystalline basement and sedimentary sequence to form the alkalic laccoliths of central Montana. The extensive volcanic rocks, radiating dikes, and sills may have formed contemporaneously with the laccoliths, or perhaps later as secondary features.

Thom (1923) suggested that the structural features of the area are the result of vertical uplift of the sedimentary sequence above deep-seated crustal blocks which produced the primary uplift-boundary faults and the general expression of domes and flexures. He infer that the localization of igneous features in c tral Montana is related to injected magmas rose along principal east-trending faults or j systems developed in the basement complex.

Sonnenberg (1956, p. 78) suggested that structural patterns represent graben-horst tions that were developed in response to re ring isostatic adjustment in the basement. Po bly the sedimentary sequence reacted passi to the differential uplift of the crustal blo and large drape structures such as those on south flank of the Big Snowy Range w formed. In addition, Sonnenberg postulate fault system trending northeast across the of the Central Montana platform and inters ing the fault systems described by Thom form an area of weakness in which the igne activity was concentrated. Gravity evidence tests to the existence of the pronounced no east-trending features that were suggested Thom and Sonnenberg.

The northern tectonic features of cen Montana are represented by residual gra anomalies in the Havre and Glasgow areas large northeast-trending elliptical anomaly present over the Bearpaw arch. This anom apparently developed in two positive segme The western high of more than +20 mgal is terpreted to be one product of a main al intrusive body that acted as a feeder to the merous intrusive features along the wes axis of the uplift and to the large surround volcanic fields. South of the western gra high is a broad positive residual anomaly a ciated with a large volcanic field. Pe (1957) suggested that the volcanic field h maximum thickness of up to 15,000 ft. eastern high is not as large in magnitude areal extent, but it averages nearly +10 m and is believed to be associated with a deep kalic body that acted as a feeder for the in sive bodies on the eastern end of the uplift. overall shape and size of the residual anom associated with the Bearpaw arch suggest th was produced by a large elongate magma b at depth and that there are two subsidiary polas near the surface that may have acte the main feeder bodies for the intrusive and trusive activity.

The zone of thrusting south of the Bear arch is coincident with a small positive res anomaly of +5 mgal. The limited exten stratigraphic displacement along the th faults in this zone, however, precludes density contrasts.

A significant positive trend northeast of the Bearpaw anomaly continues for at least 60 mi to the Saskatchewan border. This large feature is not expressed on the "Structure Contour Map of the Montana Plains," except at its southwest termination, where it coincides with the Bearpaw arch. Approximately 30 mi northeast of the Bearpaw arch, the gravity trend broadens into a +10 mgal residual anomaly that is suggestive of a northeast-trending structural feature related to a basement zone of weakness along which igneous intrusion and subsidiary basement doming may have occurred.

The Bowdoin dome is expressed by a broad regional anomaly of +10 mgal in the Glasgow area. The anomaly is elliptical, up to 35 mi long, and is approximately 20 mi southwest of the center of the dome. These relations suggest that a deep-seated upwarping fold may be offset southwest from the main surface expression of Bowdoin dome. The dome probably developed as a structural feature above a crustal block that was uplifted by an isolated igneous body at the top of the basement. Evidence for an igneous origin of the Bowdoin dome was given by Knechtel? roth (1953), who noted several igneous dikes on the dome. The location of Bowdoin dome near the trend of the Bearpaw arch suggests that it may be related to the transverse igneous belt of central Montana.

There are no distinct regional anomalies over the Little Rocky Mountains. The principal reason for their absence is the limited station distribution in the relatively small areal extent of the tectonic feature. A negative residual anomaly of up to −15 mgal north of the Little Rocky Mountains has effectively masked other smaller anomalies in the area and possibly is associated with part of the Coburg syncline.

A residual low of −20 mgal just north of the Bearpaw arch probably is related to a major basement downwarp, which may be a significant branch of the Coburg syncline. This large anomaly is suggestive of a downfaulted basin, especially along its southern boundary.

Gravity expression of the Blood Creek syncline is limited to two small residual lows and a small high, therefore, it may not have a major basement origin. The western low is aligned approximately northeast and is south of the Bearpaw arch, where a −10 mgal residual anomaly is coincident with the western part of the syncline. The central expression of the Blood Creek syncline at lat. 47°15′N and long. 107°15′W is a west-trending low of up to −5 mgal. On the east, however, the syncline is coincident with a +5 mgal high, which suggests that a deeper positive basement feature may have a more pronounced effect on the gravity field than the syncline.

The northern structural features of the Central Montana platform are expressed by large positive anomalies south of Lewistown. The Big Snowy uplift is associated with a large crescent-shaped, east-trending gravity high approximately 35 mi long and with up to a +10 mgal residual. I interpret this structural feature to have developed as an uplifted crustal block above an intrusive magma cupola.

The Moccasin and Judith Mountains north of the Big Snowy Mountains are laccolithic structures. They are expressed on the residual map by an anomaly of +10 mgal and are considered to be small near-surface alkalic intrusive bodies.

Just east of the Big Snowy anomaly is a significant residual gravity anomaly of up to +10 mgal which is situated over a complex area of structural domes and basins and is approximately 10 mi wide and 17 mi long. The relation of the overall residual gravity anomalies to the associated structural features may mean that a series of small magma chambers at depth controlled the development of the overlying subordinate domes and basins. A main chamber may have been the source of small intrusive cupolas that arched and domed the overlying sedimentary sequence into the surface domes and interspersed sedimentary basins.

Residual gravity anomalies associated with the Cat Creek anticline and the allied *en échelon* fault zone were not detected on the residual map. A zero contour line follows generally the outline of the structure near its northwest extension in the Lewistown area, but there is no evidence from the gravity anomalies of the anticline and fault zone on the southeast. The lack of a large residual anomaly associated with the Cat Creek anticline suggests that the structure and associated *en échelon* faulting are developed only to shallow depths. The Cat Creek anticline may be the result of compressive gravity sliding that is not associated directly with basement deformation.

A residual low of up to −10 mgal occurs near the east edge of the Central Montana platform (lat. 46°45′N and long. 107°30′W). It apparently masks the presence of the adjacent Cat Creek anticline and indicates that a basement feature may have a pronounced effect. The low may reflect a downwarp at the top of the basement that influenced the development of the Sumatra syncline.

Just south of the Big Snowy anomaly, a large negative residual anomaly consisting of two separate lows extends in an arcuate pattern for 65 mi from east to west. This north-curving feature of more than −10 mgal is approximately coincident on the west with the Wheatland syncline and on the east with the Willow Creek syncline. The line of gravity contours along the south part of the Big Snowy anomaly and along the south part of the adjacent positive residual anomaly on the east suggests a boundary that reflects a basement structural feature—possibly a basement fracture zone or structural hinge line, as was postulated by Sonnenberg (1956, p. 77).

A large northeast-trending positive residual anomaly occurs south of the Wheatland anomaly in the vicinity of the Women's Pocket and the Shawmut anticlines. This trend is approximately 35 mi long and has residual values of up to +10 mgal.

The Porcupine dome is partly outside of the residual gravity map. However, a positive trend of +10 mgal over the south flank of the Sumatra anticline apparently continues northeast to the Porcupine dome. The size, areal extent, and direction of the residual anomaly associated with the Sumatra anticline and the Porcupine dome suggest the presence of structural features along a major northeast-trending uplifted crustal block that possibly is related to the transverse igneous belt of central Montana.

Zietz and Hearn (1969, p. 320) gave significant aeromagnetic and gravity data for parts of the Central Montana platform. They suggested that several linear fault zones extend into the Precambrian basement and, in particular, they noted prominent northeast trends of aeromagnetic anomalies. These northeast trends corroborate the northeast trend expressed by the residual gravity anomaly patterns discussed herein. Unpublished aeromagnetic data (Zietz, 1969, personal commun.) from other parts of the western and central Montana plains also indicate marked northeast trends of regional magnetic anomalies.

Conclusions

Interpretation of gravity data from parts of western and central Montana provides a new source of information concerning near-surface, basement, and crustal structures. Known structural features are defined here in more detail, and several new basement geologic structures are indicated. Most major gravity anoma[illegible] western and central Montana are believed [illegible] associated with geologic structures that [illegible] produced principally by the Laramide o[illegible] and by Precambrian and Cretaceous-T[illegible] intrusions and extrusions.

Prominent northeast-trending basemen[illegible] tures of the western Montana plains were [illegible] tified—the Scapegoat-Bannatyne and Pe[illegible] gravity anomalies. These structures pr[illegible] are igneous ridges at the top of the bas[illegible] that may have gently arched the overlying [illegible] mentary sequence to form structural [illegible] Further, they are considered to have pro[illegible] potential petroleum-bearing flank stru[illegible] that may extend northeast from the Ban[illegible] oil field to the Canadian border.

The structural evolution of the tecton[illegible] tures in the central Montana area app[illegible] was associated directly with primary v[illegible] uplift of crustal blocks into the sediment[illegible] quence. Domes, flexures, and sedimenta[illegible] sins were formed. Significant residual [illegible] anomalies associated with several of the [illegible] and associated basins have been delinea[illegible] particular, a prominent northeast-trendin[illegible] itive anomaly, associated with the Be[illegible] arch extends northeast to the Canadian b[illegible] This anomaly may represent a major ge[illegible] structure similar in origin to those of the S[illegible] goat-Bannatyne and Pendroy anomalies.

Significant positive anomalies also are [illegible] ated with the Bowdoin dome, the Por[illegible] dome, the Big Snowy uplift, and the W[illegible] Pocket anticline. Negative anomalies, sev[illegible] which are adjacent to positive structur[illegible] tures, may represent basins of depositi[illegible] heretofore have not been explored for o[illegible] gas, particularly along basin margins.

The relation of the transverse igneous [illegible] the central Montana domal features is pr[illegible] the result of uplift caused by intrusion i[illegible] sedimentary sequence. The granitic part [illegible] crust produced the domal structural fe[illegible] that overlie uplifted crustal blocks. It [illegible] gested that the parent magma sources f[illegible] intrusive and extrusive features of the [illegible] verse igneous belt were related closely to [illegible] that produced the domal and monoclin[illegible] ures.

It is evident that the large-scale [illegible] northeast-trending anomalies of wester[illegible] central Montana are the most prominent [illegible] Bouguer and residual gravity anomaly [illegible] and are related to (1) linear trends of [illegible] bodies both at the surface and at the top [illegible]ment and (2) the structural trends of the [illegible]tral Montana area of uplifted domes and [illegible]ures. The prominent northeast trend of the [illegible]ity anomalies of the central Montana area [illegible]arallel with the structural grain of the Canadian [illegible] shield and the north-central United States. [illegible] relations suggest a similar structural ori[illegible] during the Precambrian. Major northwest[illegible]ding features are related to the Laramide [illegible]-and-thrust belt of the Montana Rockies.

[illegible]anasewich (1968) presented geophysical [illegible]ence of an east- to northeast-trending Pre[illegible]brian rift in southern Alberta and British [illegible]mbia, which supports a genetic relation of [illegible]r Precambrian structural lineaments in the [illegible]tern Montana plains with those of the [illegible]thern Alberta-British Columbia area. Aero[illegible]netic data reported by Zietz and Hearn [illegible]9) also show a prominent northeast trend [illegible] the central Montana area, which substanti[illegible] the suggestion that structural developments [illegible]ch began in the Precambrian have had a [illegible]r influence on later tectonic developments. [illegible] coincidence of the Montana Rockies [illegible] the structures of the Central Montana plat[illegible] with older sedimentary troughs of Beltian [illegible] Mississippian time suggests a common in[illegible] that has controlled both sedimentary [illegible]ition and structural development. It is [illegible]ested that a similar deep-seated influence [illegible]bly has controlled the northeast-trending [illegible]goat-Bannatyne and Pendroy trends since [illegible] Precambrian.

[illegible] is hoped that the presentation of these [illegible] data provides information and ideas [illegible] to the delineation of new areas for oil [illegible] gas exploration.

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