Gravity and Aeromagnetic Studies of the Powder River Basin and Surrounding Areas, Southeastern Montana, Northeastern Wyoming, and Western South Dakota

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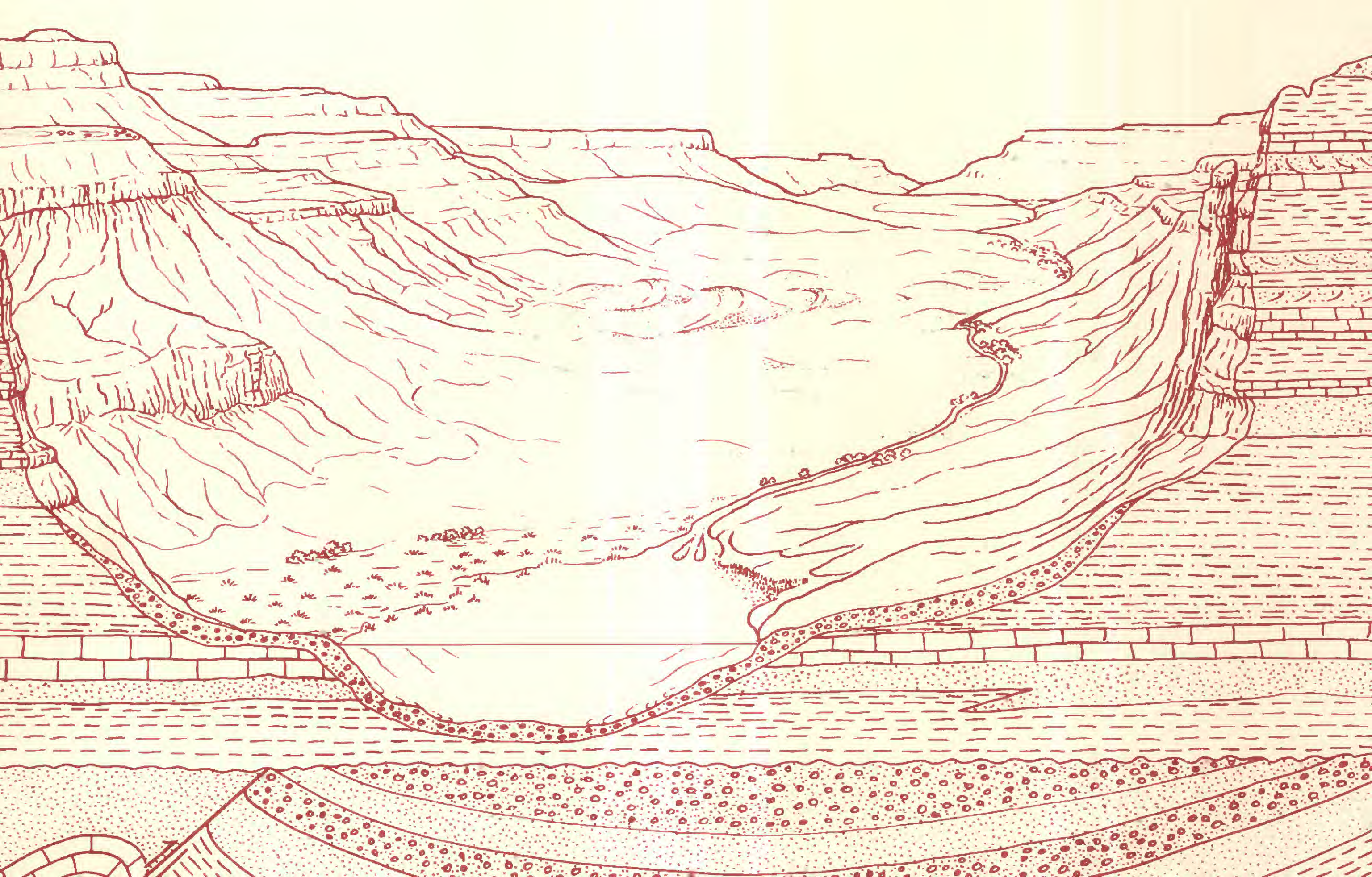

Chapter R

Gravity and Aeromagnetic Studies of the Powder River Basin and Surrounding Areas, Southeastern Montana, Northeastern Wyoming, and Western South Dakota

By STEPHEN L. ROBBINS

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

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EVOLUTION OF SEDIMENTARY BASINS—POWDER RIVER BASIN

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ABSTRACT

Complete Bouguer anomaly, isostatic residual anomaly, and horizontal gradient anomaly gravity maps of the Powder River Basin and surrounding areas in southeastern Montana, northeastern Wyoming, and western South Dakota were compiled using gravity data from 21,528 stations. A total-intensity anomaly aeromagnetic map with 3 mi (5 km) spaced east-west flight-lines is also presented. Analyses of these maps and data show that (1) most of the crystalline basement of the study area is composed of Archean rocks with a small arc-shaped area on the southeast-east side that is probably composed of Proterozoic or younger rocks, (2) the mountains ranges in the study area lack a local isostatic root (although regionally the study area is in equilibrium) and were formed by low-angle thrusting that flattened into the middle or lower crust during the Laramide orogeny, (3) major lateral lithologic differences occur in the upper basement (Archean) rocks beneath the Powder River Basin and within the Miles City arch, (4) within the subsurface in the Bighorn Mountains there is a major contrast in the physical properties of the rocks across the Ten Sleep fault-Crazy Woman Creek lineament, (5) the Black Hills may consist of three separate blocks with the southeastern one sitting on a younger and less magnetic basement with no apparent volcanism associated with it, and (6) late Paleozoic and Mesozoic sedimentary rocks decrease in density values from west to east; this probably correlates with a decrease in overall thickness of these rocks.

INTRODUCTION

This report is a presentation and analysis of gravity and aeromagnetic maps in and around the Powder River Basin (PRB) in southeastern Montana, northeastern Wyoming, and western South Dakota. The maps include (a) complete Bouguer anomaly (CBA) gravity (pl. 1), (b) 250 km low-pass filtered isostatic residual anomaly (IRA) gravity (pl. 2), (c) horizontal gradient anomaly (HGA) gravity with structural contours on the top of the Precambrian basement (pl. 3), and (d) total-intensity anomaly aeromagnetic (pl. 4). The mapped area is between lat 42° and 47° N. and long 104° and 108° W. (fig. 1).

The map area includes the PRB and the surrounding physiographic and structural uplifts, which all influenced the evolution of the Basin. These uplifts include the Bighorn Mountains, the Black Hills, the Casper arch, the northern Laramie Range, the Hartville uplift, the Hardin platform, the Miles City arch, and the Porcupine dome (fig. 1). Other uplifts shown in figure 1 are outside of the study area.

The PRB is one of the major broken foreland sedimentary basins of North America and underlies an area of about 30,000 km^2. It is part of the Laramide intermontane basin province in the middle Rocky Mountains and was formed during the later part of the Laramide orogeny in early Tertiary time (Hamilton, 1988; Perry and others, 1992). The Basin is asymmetric in shape, elongate in the north-south direction, with the Basin axis on the west side (see structural contours on pl. 3).

The PRB has long been known as a prolific hydrocarbon producing area (Slack, 1981) and is also a large major producer of coal (Mallory, 1972). However, the lower Paleozoic rocks, in the area, remain little studied (Macke, 1993) and few geophysical studies have been published. The only seismic studies published in this area prior to the USGS ESB program (Grow and others, 1988; Miller and others, 1988; Robbins and Grow, 1990) are Andrew (1985), Moore (1985), Stone (1983), and Welch and Taylor (1985). The only published aeromagnetic study in the Basin is Duval and others (1977). Gravity studies

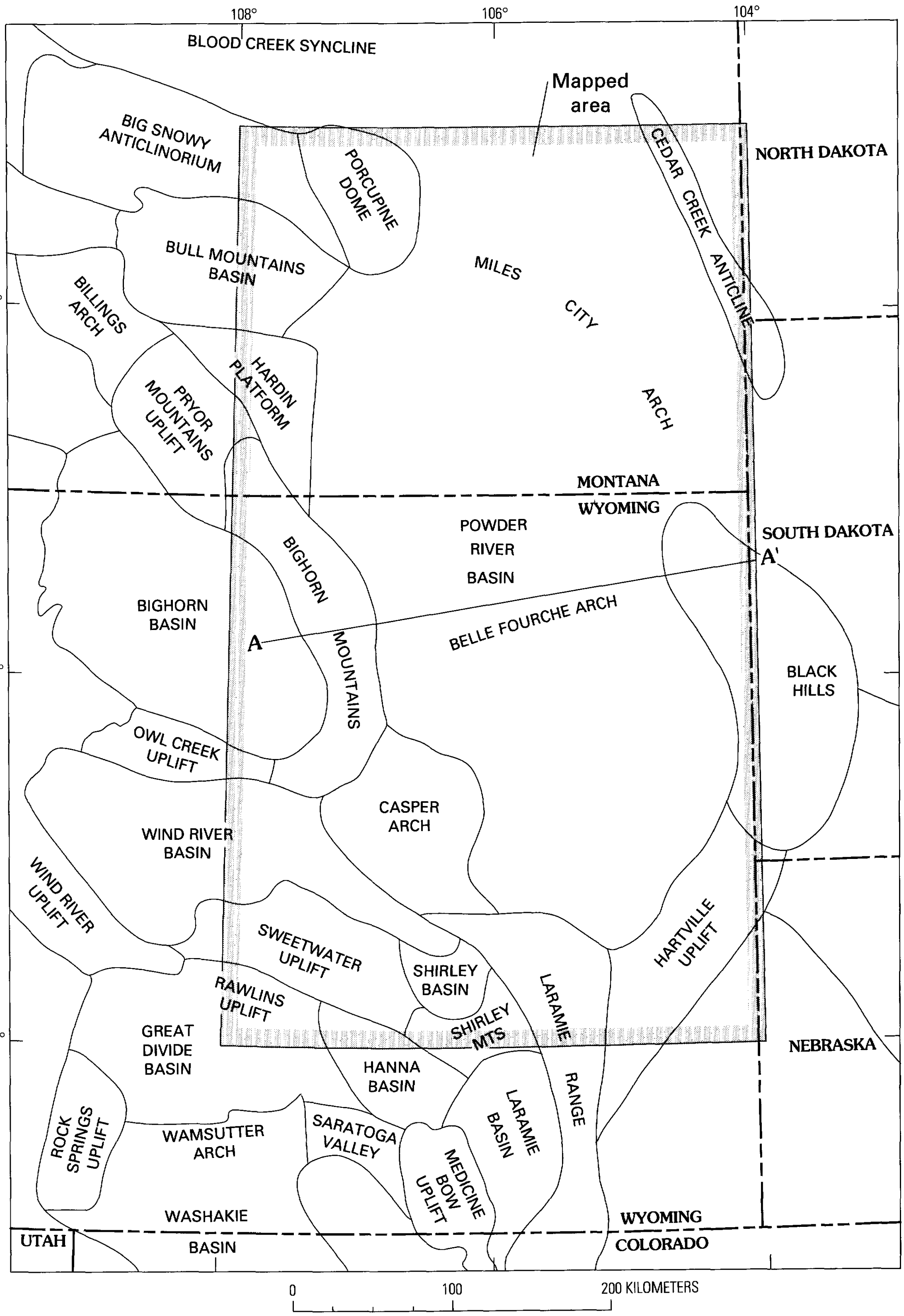

Figure 1. Map showing physiographic features in study area. Modified from Grose (1972). Gravity and magnetic profile line *A–A'* is also shown in figure 6.

prior to the ESB program (Robbins, 1988, 1991) are limited to Black and Roller (1961), Kleinkopf and Redden (1975) and Slack (1981).

There are, however, a few regional geophysical studies that include the PRB. These include Strange and Woollard (1964), Malahoff and Moberly (1968); Zietz and others (1968; 1980), Rush and others (1983), Jachens and others (1989), and Robbins and Grow (1992). Other studies that are relevant because they discuss similar structural styles associated with nearby intermontane basins and uplifts are Bonini and Kinard (1983); Case and Keefer (1966); Grannell and Showalter (1991); Gries and Dyer (1985); Hurich and Smithson (1982); Johnson and Smithson (1985); Sharry and others (1986); and Skeen and Ray (1983).

In this report, I present new compilations of complete Bouguer anomaly, isostatic residual anomaly, and horizontal gradient anomaly gravity maps of the PRB and surrounding areas at a scale of 1:1,000,000. Although there is a lack of data in a few parts of this region, these are the first color gravity maps at this scale. The discussion begins with a summary of the tectonic history of the region from Early Archean time; this is followed by a description of the geophysical data and a discussion of the rock density and rock magnetic susceptibility data used in the interpretation models in this report. The geophysical discussion focuses on the anomalies as seen on these new maps and the interpretation of the gravity and magnetic profile across the area (fig. 6), and their implications for tectonic and isostatic processes.

SUMMARY OF THE TECTONIC HISTORY

The present configuration of the Powder River Basin (PRB) was formed structurally during the Late Cretaceous-early Tertiary Laramide orogeny. Many of the rocks of the surrounding uplifts are of Precambrian age and the basement beneath the PRB is assumed to contain rocks of similar age. Unconformably overlying these basement rocks are Paleozoic cratonic-shallow-water marine-sedimentary rocks of up to 1 km in thickness (Mallory, 1972); overlain by more shallow-water cratonic marine rocks interfingered with floodplain deposits (as much as 0.5 km in thickness; Mallory, 1972) through Jurassic time. In Cretaceous time, the Basin was part of an inland sea that covered much of central North America and from which shallow-water marine and coastal plain sediments (up to 3 km in thickness; Mallory, 1972) were deposited. The upper most sedimentary rocks in the PRB are of early Tertiary age and are mostly fluvial and lacustrine deposits (0.6 to 2.0 km in thickness) and are exclusive to this Basin; whereas, older rocks within this Basin have correlatives in surrounding basins. Detailed discussions of the Phanerozoic sedimentary rocks in this Basin can be found in other chapters in this Bulletin series (B–1917). Here, I will attempt to summarize the tectonic events that occurred in this area as outlined in table 1.

Precambrian

Radiometric dating of detrital zircons from a quartzite in the Beartooth Mountains in Montana suggest that a major phase of crust formation in the area (the Wyoming Precambrian province) occurred at about 3.3 Ga, and that this crust was formed from older crustal components as old as 3.96 Ga (Mueller and others, 1992) (table 1). Whether or not crust of this age is present in the province today is not known. However, this age (3.96 Ga.), according to Mueller and others (1992), is equivalent to the Acasta gneisses of the Slave province (the oldest known rocks in North America). The 3.3 Ga crust was in part composed of granite-gneiss terranes (Condie, 1976). Subsequent to this crustal formation, "Eugeoclinal-type" sedimentation (including the deposition of the quartzite from which the detrital zircons were taken) and volcanism dominated until 2.9 Ga. Between 3.0+ and 2.9+ Ga, the first recorded tectonic events occurred with deformation, metamorphism, and plutonism (including basaltic dikes) in the Bighorn Mountains and northern Laramie Range and with metamorphism in the Hartville uplift (Condie, 1976; Hedge and others, 1986; Snyder and others, 1989). Granitic and mafic emplacement continued in the Bighorn Mountains between 2.9 and 2.75+ Ga. Metamorphism continued in the Hartville uplift until 2.65 Ga (Hedge and others, 1986). Mueller and Wooden (1988) suggested, from evidence in the Beartooth Mountains, that at about 2.8 Ga the northern edge of this province may have been the site of a convergent continental margin. Between 2.7 and 2.6 Ga (table 1), widespread deformation, metamorphism, and plutonism occurred (Condie, 1976). Granitic intrusions continued on to 2.5 Ga (end of the Archean) in the Hartville uplift and the northern Laramie Range. Granitic intrusions first appeared in the Black Hills at the end of the Archean and continued into earliest Proterozoic (Hedge and others, 1986). Knight (1990) believes that much of the above succession was derived from a volcanic island arc.

The earliest Proterozoic tectonic activity occurred about 2.25 to 2.15 Ga (table 1) when diabase dikes intruded the Bighorn Mountains (Condie, 1976; Hedge and others, 1986). Although these and the previous dikes trend northeast, northwest, east-west, north-northwest, north-northeast, and east-northeast (Snyder and others, 1989), the northeast trends seem to predominate (Love and Christiansen, 1985). These intrusions were followed by 2.1–1.9 Ga granitic intrusions in the Hartville uplift area. Cavanaugh and Seyfert (1977) believe that the Wyoming

Table 1. Ages of tectonic events for the Powder River Basin and surrounding areas, southeastern Montana, northeastern Wyoming, and western South Dakota

[Ages given in logarithmic scale]

Age		Structural activity	References
Tertiary	0.02		
		Regional uplift	DeWitt and others, 1986
	0.05	Igneous extrusives Laramide Orogeny	DeWitt and others, 1986; Perry and others, in press
K		Hartville Uplift, fault displacement, southern area of basin rising	Merewether, in press
	0.1		
		Renewed block fault activity on the Precambrian lineaments creating the Belle Fouche Arch	Slack, 1981
J			
	0.2		
Ʀ		Tectonic event } Successors to ARM	Maughan, 1990
P		Tectonic event }	
IP	0.3	Third event } Ancestral Rocky Mountains (ARM) epeirogeny	
		Second event } Normal faulting	Slack, 1981 Maughan, 1990
M		First event }	
D		Tectonic event–Upwarping–Precursor for ARM	Macke, in press; Maughan, 1990
	0.4	Tectonic event–Upwarping	
S			Macke, in press
O		Tectonic event–Upwarping	Macke, in press
	0.5		
C		Normal faulting (extension or left-lateral transtension)	McMillen, 1989
Proterozoic	0.6		
	1.0		
	1.5		
		Granitic intrusions (Black Hills and Hartville uplift)	Condie, 1976; Hedge and others, 1986; and Mueller and others, 1992
	2.0	Granitic intrusions (Hartville uplift)	
		Diabase dike swarms (Bighorn Mountains)	
		Granitic intrusions (Black Hills, Hartville uplift, and N. Laramie R.)	
Archean	2.5	Widespread deformation, regional metamorphism, and plutonism	
		Granitic and mafic intrusions (Bighorn Mts and N. Laramie Range)	
		Deformation, granitic emplacement, regional metamorphism, and diabase dike intrusions	
	3.0	Dominantly eugeoclinal sedimentation and volcanism	
		Major phase of crustal formation in province	
	4.0	Oldest crustal components found in province	
	B.Y.A.	Approximate age of Earth	

province has been part of the Superior province for at least the past 2.75 b.y. They stated that at about 1.75 Ga, the Slave province to the north joined with the Superior province. Hills and Houston (1979) suggested that, at about this same time (1.725–1.635 Ga), an Atlantic-type margin existed at the south and east edges of the study area, which then collided with and was partially subducted beneath a volcanic arc. This subduction zone dipped toward the southeast. 1.7–1.6 Ga intrusions in the Hartville uplift and the Black Hills (table 1) (Hedge and others, 1986) may be related to one or both of the above events. During the remainder of the Proterozoic, no other known tectonic activity took place in the region. However, the area was eroded to a low relief surface upon which Phanerozoic rocks were later deposited. It has been suggested (Stewart, 1976; Winston, 1988) that rifting to the west of this province was initiated about 0.85 Ga, thus forming a passive continental margin by about 0.65 Ga.

There are numerous northeast-trending structural lineaments within the Basin, with differential vertical uplift of up to 100 meters (primarily during Cretaceous time) possibly that some believe to be basement shear zones that have moved several times in the Phanerozoic (Slack, 1981; Maughan, 1983). These lineaments, although not seen on Blackstone's (1990) Precambrian basement map, may have been in existence by 1.6 Ga. Slack (1981) believes that these lineaments may be analogous to a shear zone that is believed to be the result of the development of the Atlantic-type margin at about 1.7 Ga.

Paleozoic Era

McMillen (1989) interpreted normal faults in the Middle to Upper Cambrian sequence from seismic reflection data within the Basin. He believes these faults were caused by northeast-southwest extension or east-west left-lateral transtension. Macke (1993) divides the Cambrian through Mississippian rocks into five depositional sequences each separated by erosion and unconformities. Although the PRB area was well removed from the continental margins during this time interval, tectonics of the margins drove structural development within the craton in the form of up- and down-warping that shaped the above sequences. The upwarping formed the tectonic elements that allowed for the periods of erosion at the approximate times of 490, 390, 365, and 330 Ma (table 1).

In the Paleozoic, the region had no marked relief and the shelf cycled below and above sea level a number of times. Maughan (1990) summarizes the tectonic events in the area that are associated with the ancestral Rocky Mountains (ARM) orogeny. He stated that the above events at about 365 and 330 Ma were precursors to the ARM orogeny (table 1). These precursors were then followed by three major events; the first in latest Mississippian to earliest Pennsylvanian time, the second during Middle Pennsylvanian time, and the third (a weaker event) in Late Pennsylvanian to Early Permian time. Two successive events, one in late Early Permian and the other in Late Permian finished out the ARM orogeny. Minor rejuvenation along the Precambrian lineaments appears to have occurred during the Middle Pennsylvanian (Slack, 1981).

Mesozoic Era

Deposition in the Late Permian continued into the Triassic in the region, with four marine transgressions from the west into an easterly low-energy nonmarine depositional environment (Johnson, 1993). The boundary between Permian and Triassic rocks is within the Goose Egg Formation and is not evident. Multiple changes in sea level continued throughout the Triassic and Jurassic. Six lithostratigraphic units with three intervening erosional events have been identified within the Triassic, and five marine inundations and six intervening erosional events have been recorded for the Jurassic (Johnson, 1992, 1993). During this time period, a larger amount of continental floodplain rocks were deposited compared with the Paleozoic Era. However, the broad flexing of the craton appears to still be the only tectonic activity.

In the Early Cretaceous, tectonic activity increased with the reactivation of the basement lineaments with the subsequent creation of the Belle Fourche arch (fig. 1) in the central part of the PRB (Slack, 1981) (table 1); thus, influencing the character of the Basin strata in early Late Cretaceous. This increased activity may have been related to the Sevier orogeny that was in progress to the west. Also in early Late Cretaceous time (about 91 to 87 m.y. ago), the Hartville uplift was rising, a northeast-north-trending area in the southern part of the Basin was also rising, and displacements occurred along west-trending faults in the southwestern part of the Basin (Merewether, oral commun., 1992). During the Late Cretaceous, deformation in the region was recurrent and generally minor; possibly in response to the beginnings of the Laramide orogeny that began over 90 m.y. ago in southwest Montana (Perry and others, 1992). Laramide deformation proceeded in an eastward and southward direction, reaching the PRB area in the early Tertiary with the uplift of the Bighorn Mountains and Black Hills.

Cenozoic Era

The Laramide orogeny was a period of major crustal unrest when compressional forces produced basement uplifts of up to 8–10 km or more (Robbins and Grow, 1992) and formed the modern day Rocky Mountains and

PRB. Uplift of the Bighorn Mountains and the Black Hills began in the middle to late Paleocene (D.A. Seeland, oral commun., 1992). The orogeny ended in early to middle Eocene (DeWitt and others, 1986; D.A. Seeland, oral commun., 1992) (table 1). During this time period, the northern Black Hills were intruded by a west-northwest trending belt of igneous stocks, laccoliths, dikes, and sills (DeWitt and others, 1986). During the Oligocene, much of the region was covered with a thin sequence of terrestrial sediments. Miocene and Pliocene sediments are present in many areas surrounding the Basin and may or may not have been deposited within the PRB. The area has undergone post 30 Ma uplift and erosion that has created much of the relief as seen today and that is still continuing today. Since Mesozoic time, up to 20 km of crustal thickening has occurred in the Rocky Mountain foreland. Tertiary sedimentation and Laramide strain can account for only 15 percent of this thickening (Bird, 1984). It is believed by some, including Bird (1984) and Dickinson and others (1988), that some of this thickening and subsequent uplift was caused by subduction of a subhorizontal slab of oceanic crust between about 70 and 40 Ma, and the continued uplift was caused by delamination of this crust and emplacement of anomalously warm mantle, subduction of an oceanic spreading center, or creation of a slab window.

GEOPHYSICAL DATA

Complete Bouguer anomaly (CBA), isostatic residual anomaly (IRA), and horizontal gradient anomaly (HGA) gravity maps of the Powder River basin (PRB) are presented in plates 1, 2, and 3. These maps were generated using 21,528 data points. Most of these data are from the U.S. Defense Mapping Agency (DMA) files, St. Louis, Mo. I occupied 1,532 gravity stations in eastern Wyoming and southeastern Montana to fill in holes in the coverage, and Jenkins (1986) collected 61. Principal facts for 1,323 of these gravity stations are published in Williamson and Robbins (1991, 1993) and were used along with the DMA data to compile CBA gravity maps of the Sheridan, Gillette, and Newcastle 1°×2° quadrangles (Robbins, in press; Robbins and Williamson, in press-a, in press-b). Principal facts for the 270 stations located on the Arminto, and Torrington 1°×2° quadrangles have not yet been released.

All gravity values are based on the International Gravity Standardization Net (IGSN)-1971 datum (Morelli, 1974), and the data were reduced using the Geodetic Reference System (GRS)-1967 formulas (International Association of Geodesy, 1971) with an assumed average crustal density of 2.67 g/cm^3. The terrain effect out to a distance of 167 km from each station was removed using the computer program BOUGUER (Godson and Plouff, 1988). The terrain effect for my stations was removed by manually making corrections to a distance of 0.59 km and using the computer program from there out to 167 km. Isostatic corrections were made using a computer program by Simpson and others (1983) assuming an Airy-Heiskanen compensation model where the parameters used are (1) density of the topographic load = 2.72 g/cm^3, (2) depth of compensation below sea level = 40 km, and (3) density contrast at the crust-mantle boundary = +0.35 g/cm^3. The objective of calculating isostatic corrections is to generate a gravity map that is most representative of lateral density variations in the upper crust only; that is, the removal of the regional field from the CBA map that depicts lateral variations in the density of the entire lithosphere. However, Wyoming is an area (due to the large thrust-blocks that make up many of the mountains in the area) where a local Airy-Heiskanen model that assumes a root is not optimum. Therefore, I used, in calculating these corrections, a digital topography model that had been filtered through a 250-km low-pass computer program. This I have found is the best filter for removal of the long wavelength components of the gravity field in this area and appears to have generated an improved IRA map (Robbins and Grow, in press).

The CBA and IRA gravity maps were generated by gridding and plotting the scattered data using the computer program "Interactive Surface Modelling" by Dynamics Graphics, Inc., Berkeley, Calif. A 2.5 km grid interval was used to plot the CBA and IRA maps (pls. 1 and 2). The HGA map (pl. 3) was generated from the IRA grid file using a package of programs called BOUNDARY based on that of Blakely and Simpson (1986). The maps are plotted at a scale of 1:1,000,000. Station location spacing is quite variable and the locations are shown on the CBA map (pl. 1). The CBA and IRA maps are contoured at 2 1/2 mgal and HGA map is contoured at 1 mgal per km.

One use of HGA maps is to aid in the interpretation of fault geometry. Since interpretation of the HGA map (pl. 3) is best accomplished by comparing the locations of the maximum gravity gradients with the surface traces of faults (that is, the position of the maximum gravity gradient is dependent primarily on the fault angle) (fig. 2), I have included the Precambrian basement structure contours and fault traces for the region on this map. Figure 2 shows an idealized two-body fault-contact model representing a typical uplifted mountain adjacent to a deep basin where the basin is 6 km deep and the density contrast is -0.2 g/cm^3 with respect to the surrounding basement rocks. Examples for six fault dip angles (70° normal, vertical, and 20°, 30°, 45°, and 60° reverse) show that the position of the maximum gradient is directly over a vertical fault, that the maximum gradient position is displaced toward the mountain range (with respect to the surface trace of a fault) for reverse faults and toward the basin for

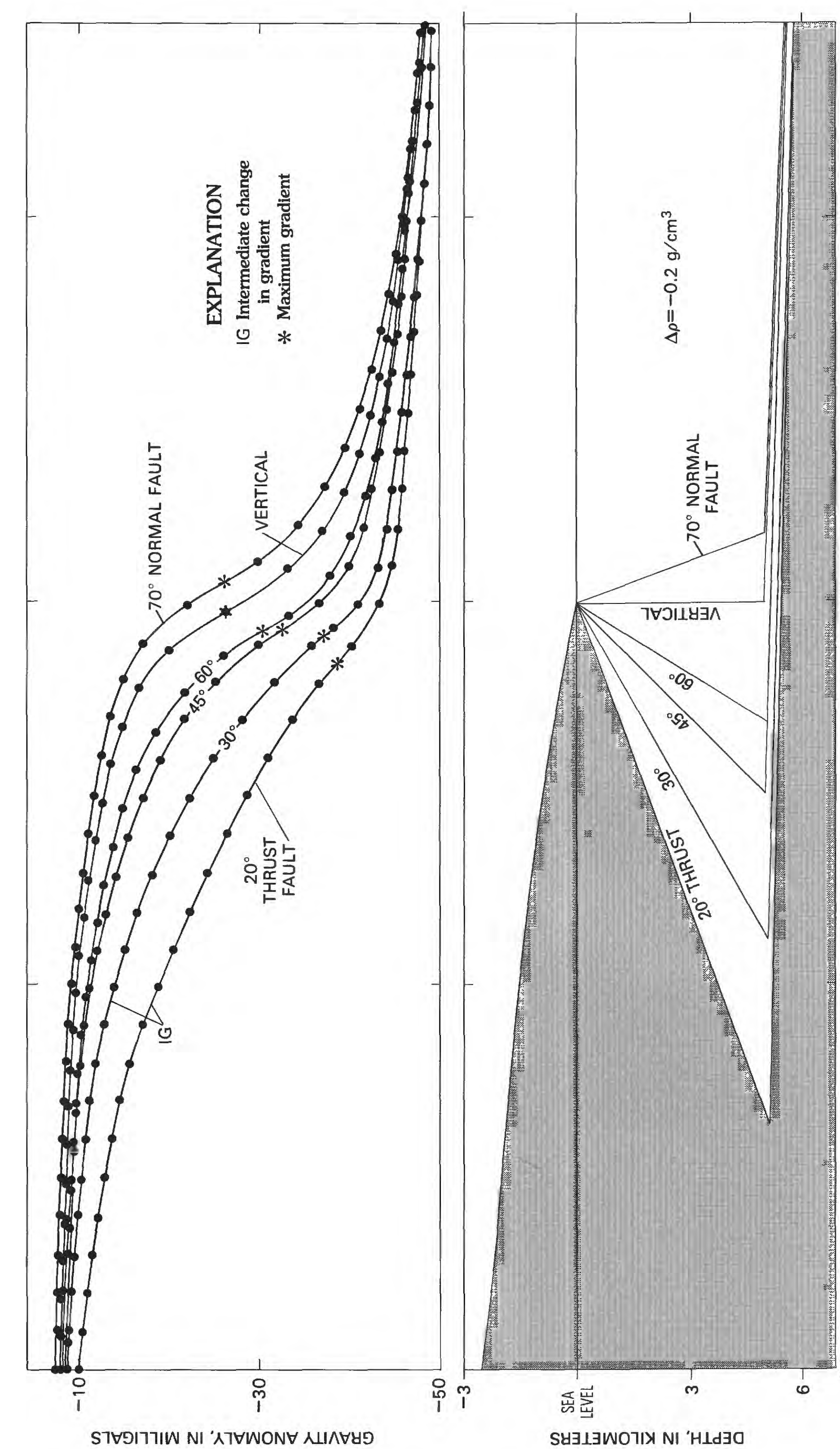

Figure 2. Gravity anomaly-fault dip comparison model.

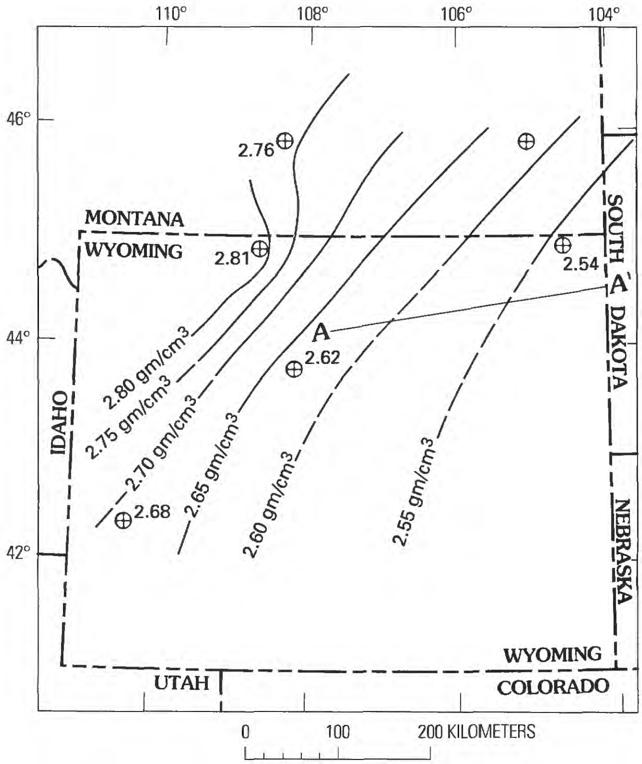

Figure 3. Map showing density variations within Paleozoic rocks from borehole gravity meter data. Gravity and magnetic profile line *A–A'* is shown in figure 6.

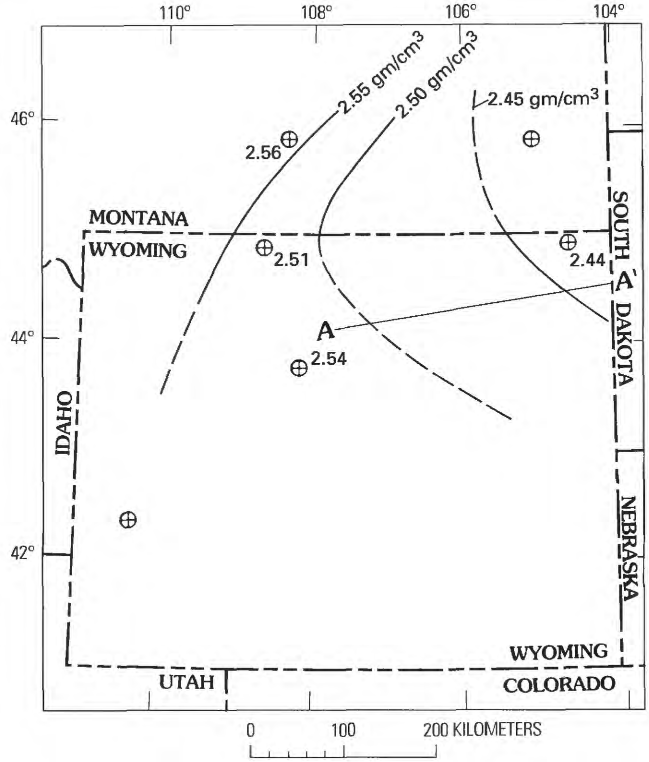

Figure 4. Map showing density variations within Triassic and Jurassic rocks from borehole gravity meter data. Gravity and magnetic profile line *A–A'* is shown in figure 6.

normal faults. Although the maximum gradients are within 2 km of the surface trace in all six cases, intermediate changes in the gradients are displaced 10–15 km toward the range for the low-angle thrusts (20° and 30°) (Robbins and Grow, 1992; see IG locations in fig. 2).

The total-intensity anomaly aeromagnetic map (pl. 4) was compiled by Rush and others (1983) using previously published National Uranium Resource Evaluation (NURE) data. The NURE maps are published at a scale of 1:250,000, and Rush and others published their map at 1:1,000,000. Their map did not include the northern tier (lat 46° N. to 47° N.), which I added using published NURE data (U.S. Dept. of Energy, 1981, 1986).

ROCK UNIT PHYSICAL PROPERTIES

Density data are necessary in any quantitative interpretation of gravity data. However, data from very few density measurements on the rock units in this and surrounding areas have been published. The most reliable values for Precambrian rocks in Wyoming are from core samples from a 4 km deep borehole in the Wind River Mountains and from surface samples in the Laramie Mountains (Smithson, 1971). Mean values for these two areas are 2.70 and 2.75 g/cm^3, respectively. Hurich and Smithson (1982), based on these measurements, assumed an average mean for the Precambrian in the Wind River Mountains of 2.73 g/cm^3, which is the value I used for the Precambrian in this study area. The only published density values in sedimentary rocks from the Powder River Basin (PRB) are from borehole gravity meter (BHGM) surveys in Kososki and Robbins (1979, 1980b). The values in Kososki and Robbins (1979) (from a well at the eastern edge of the Basin in Wyoming near the Montana border) were the ones used to model figure 6. Other BHGM surveys within the Laramide intermontane basin province are in Beyer and Clutsom (1978a, 1978b, 1980) and Kososki and Robbins (1980a). These surveys were in wells that only penetrated sedimentary rocks of Cambrian through Cretaceous in age. Density values from the BHGM surveys have been averaged for Paleozoic, Triassic-Jurassic, and Cretaceous age sedimentary rocks and have been plotted in figures 3, 4, and 5, respectively. Each of these figures shows a decrease in density values from west to east.

The most comprehensive density studies within the Laramide province are in Bankey and Merewether (1990) (Green River, Great Divide, and Washakie Basins) and Hurich and Smithson (1982) (Green River and Wind River Basins). Other studies include Karasa (1976) (Wind River Basin), and Parks (1979) (Green River and Wind River Basins). Inspection of the density values in these studies show the values of the sedimentary rocks to be higher than the ones I am using in the PRB.. This agrees with the above noted decrease in density values from west to east.

Magnetic susceptibility data are necessary in any quantitative analysis of magnetic maps. Most sedimentary rocks, included within this study area, have susceptibilities of or near zero. The only rocks within the area with any significant magnetic signature are some of the Precambrian crystalline basement rocks and possibly the Eocene volcanic rocks in the northeast part of the study area. Only two publications were found that contained magnetic property values for Precambrian rocks (Kiilsgaard, 1972; Jackson, 1976). These values are for only nine samples in the Bighorn Mountains. The values are quite variable and range from 287×10^{-6} to $4{,}540\times10^{-6}$ cgs (centimeter-gram-second) units. Because there was no apparent grouping of susceptibility values, the values used in figure 6 for the magnetic model, were based on best fits to the gravity modeling and range from 20×10^{-6} to $3{,}200\times10^{-6}$ cgs units.

GEOPHYSICAL DISCUSSION

The complete Bouguer anomaly (CBA) gravity map (pl. 1) depicts lateral variations in the density of the entire lithosphere that accounts for the dominant regional gravity gradient from northeast to southwest. This gradient is even more evident on the CBA gravity map of Wyoming (Robbins and Grow, 1992) and is a direct reflection of the topographic gradient. However, the inferred regional dip of the Moho based on refraction data (Braile and others, 1989) is from a depth of about 35 km in southwestern Wyoming to about 50 km in northeastern Wyoming, which is opposite to what the gravity gradient suggests, assuming a homogeneous crust. Therefore, the crust and possibly upper mantle must be dominated by lateral density variations that allow the Moho to rise to the southwest. Both crustal and upper mantle compressional seismic velocities are lower in the southwest than in the northeast and thus support the inference of lateral density changes.

Because this discussion is mainly interested in density variations only in the upper crust, the focus here is on gravity anomalies as seen on the 250 km low-pass filtered isostatic residual anomaly (IRA) gravity map (pl. 2).

Regionally, all of the IRA gravity anomalies over the mountain ranges are seen as large highs. This is caused by dense Precambrian rocks at or near the surface within these mountains and the magnitude of the highs implies that these ranges are rootless since mountains with roots would have anomalies at or near zero over them. The gradients (pl. 3) associated with these gravity highs also suggest that these ranges were formed by major low-

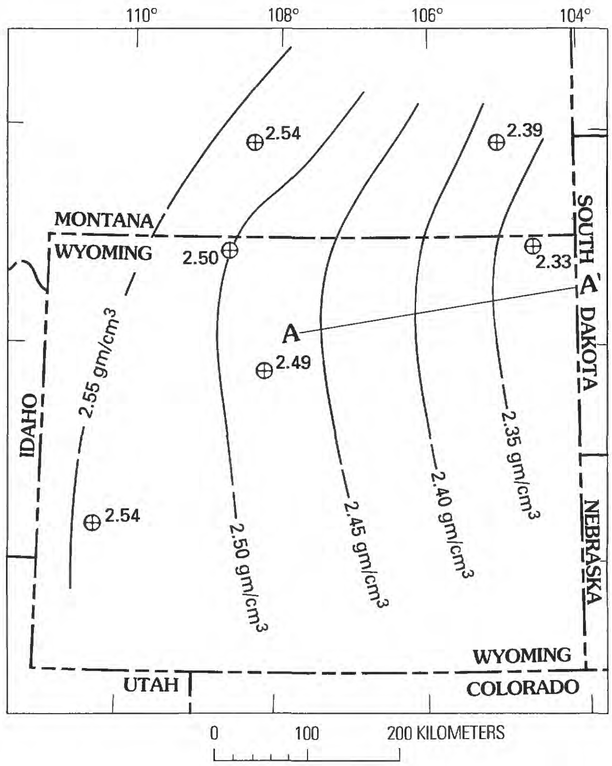

Figure 5. Map showing density variations within Cretaceous rocks from borehole gravity meter data. Gravity and magnetic profile line *A–A′* is shown in figure 6.

angle thrusting (fig. 2). The gravity lows are centered over the deeper parts of the foreland basins and are caused by thick low-density sedimentary rocks that fill the basins. Both the gravity low (pl. 2) and the structure contours (pl. 3) show the Powder River Basin (PRB) as not being as deep as the Wind River, Hanna, or Great Divide Basins. The average of the IRA gravity values across the study area is near zero, thus indicating that the region as a whole is at or near isostatic equilibrium (pl. 2). However, the large gravity highs over the mountain ranges suggest that locally they are not in equilibrium.

The total-intensity anomaly aeromagnetic map (pl. 4) features two provinces that are separated by roughly the -400 gamma contour line on the east and southeast portion of the map. The west-northwest province is part of a roughly circular magnetic feature (although not evident on this map) centered over much of Wyoming at overall elevated magnetic values (Rush and others, 1983). This feature is expressed by collective arcuate contour trends and may be caused by and roughly coincides with the Archean basement that is present within most of the area. The east-southeast province is probably of Proterozoic basement, and the low magnetic values within the map area may reflect an old subduction zone.

The gradients of most of the magnetic highs in the PRB (pl. 4) suggest that the magnetic sources are fairly close to the surface (upper few kilometers). However, the anomalies at locations B, M, and N are larger in both amplitude and wavelength and suggest larger, deeper (basement) sources with the north-south trending anomaly P extending from the near surface to some greater depth.

Powder River Basin

Drill hole and seismic reflection data (Moore, 1985; Blackstone, 1990) show that the Phanerozoic sedimentary rocks within the PRB dip gently to the west on top of the basement surface with only small vertical displacements trending in a north-east direction (Slack, 1981). These offsets (<60 m) have been active intermittently throughout Phanerozoic time and have controlled the location of numerous hydrocarbon deposits. Although the gravity lows within the PRB (pls. 1 and 2) tend to be located over and mimic the actual Basin lows, inspection of the IRA gravity map (pl. 2) and the aeromagnetic map (pl. 4) reveals large short-wave-length gravity and magnetic highs, such as anomalies M, N, and P, that do not represent any structure within the Basin's sedimentary section. Figure 6, an west-east gravity and magnetic profile and computer model across the Bighorn Mountains, the central PRB and the Black Hills, is an attempt to synthesize the Basin structure and upper Precambrian basement (Robbins and Grow, 1992). In order to fit the observed gravity and magnetic curves over the PRB, density values for rocks within the upper basement must range between 2.58 and 3.01 g/cm^3 assuming the normal basement density for the area is 2.73 g/cm^3, and the magnetic values must range between 20×10^{-6} and $3,200\times10^{-6}$ cgs units. This implies that significant lithologic heterogeneity exists in the upper part of the basement beneath this Basin.

South of the west-east profile shown in figure 6, within the PRB, is the Belle Fouche arch (fig. 1). The existence of this arch is only barely suggestive on the Precambrian structure maps (pl. 3), which supports Slack's (1981) findings that the total vertical displacement on the arch is less than 60 m. However, both gravity (pl. 2) and magnetic (pl. 4) anomaly highs are located over parts of this arch, thus suggesting that mafic intrusions into the basement during the Phanerozoic may have contributed to the development of this arch. A similar looking gravity high exists north of Sheridan, Wyoming, that may be caused by a similar intrusion.

Bighorn Mountains

The Bighorn Mountains were formed during the Laramide orogeny by major basement-involved thrusting. Seismic profiles across the east flank of the mountains show that two major west-dipping thrust faults are present just west of Buffalo, Wyoming (Robbins and Grow, 1992). The dominant thrust dips 20°–30° to the west and has 6–11 km of basement overhang onto the PRB. The smaller fault (Buffalo Deep, fig. 6) (Blackstone, 1981) is a few kilometers east of the main mountain front and has less than 1 km of offset. There have been two wells drilled (pl. 3) vertically through Precambrian granite into PRB sedimentary rocks. The Arco Kenney Ranch well (T. 50 N., R. 83 W., sec. 4), west of Buffalo, Wyoming, penetrated about 1 km of granite before entering PRB sedimentary rocks. The Gulf Granite Ridge well (T. 53 N., R. 84 W., sec. 9), located about 20 km northwest of Buffalo, penetrated 1.8 km of granite before entering sedimentary rocks.

Figure 6 (a combined gravity and magnetic model along profile A–A′), which incorporates some analyses by Jenkins (1986), clearly shows a good correlation between my interpretations of the gravity and magnetic data and the results from the seismic profiles (Robbins and Grow, 1992). The location of the maximum gravity gradient on plate 3 (HGA map) is on the mountain side of the surface fault trace and is another indication for a low-angle fault to the west along this mountain front (fig. 2). This model and earlier discussions suggest that this fault and other basement-involved thrust faults within the Laramide province flatten out within the middle or lower crust (Sharry and others, 1986; Robbins and Grow, 1992).

The gravity high (pl. 2), located over the exposed Precambrian rocks (anomaly A), is divided into two lobes. The north lobe (the one with the higher amplitude) is located over Archean granitic rocks, and the south lobe is located over Archean gneisses (Heimlich, 1969). On the aeromagnetic map (pl. 4), the magnetic signatures are different over each of the two rock types with the southern bodies appearing to contain less magnetic material.

Within the southern part of the gneiss bodies is the Ten Sleep fault (pl. 3) connecting on the east into a possible lineament along Crazy Woman Creek (southeast of anomaly C). The aeromagnetic map (pl. 4) shows a low over this zone and the southern extent of the gneisses. The IRA gravity map (pl. 2) shows a small gradient over part of the fault-lineament zone, but a lower amplitude high still remains to the south suggesting that Precambrian rocks are still present on the south but in the form of a thinner slab.

Black Hills

The Black Hills have been referred to as an elongate dome or doubly plunging anticline that was domed during the Laramide orogeny (Kleinkopf and Redden, 1975; DeWitt and others, 1986). Actually, it consists of two separate blocks separated by the Fanny Peak monocline (pl. 3) at the east edge of our study area. The southeastern

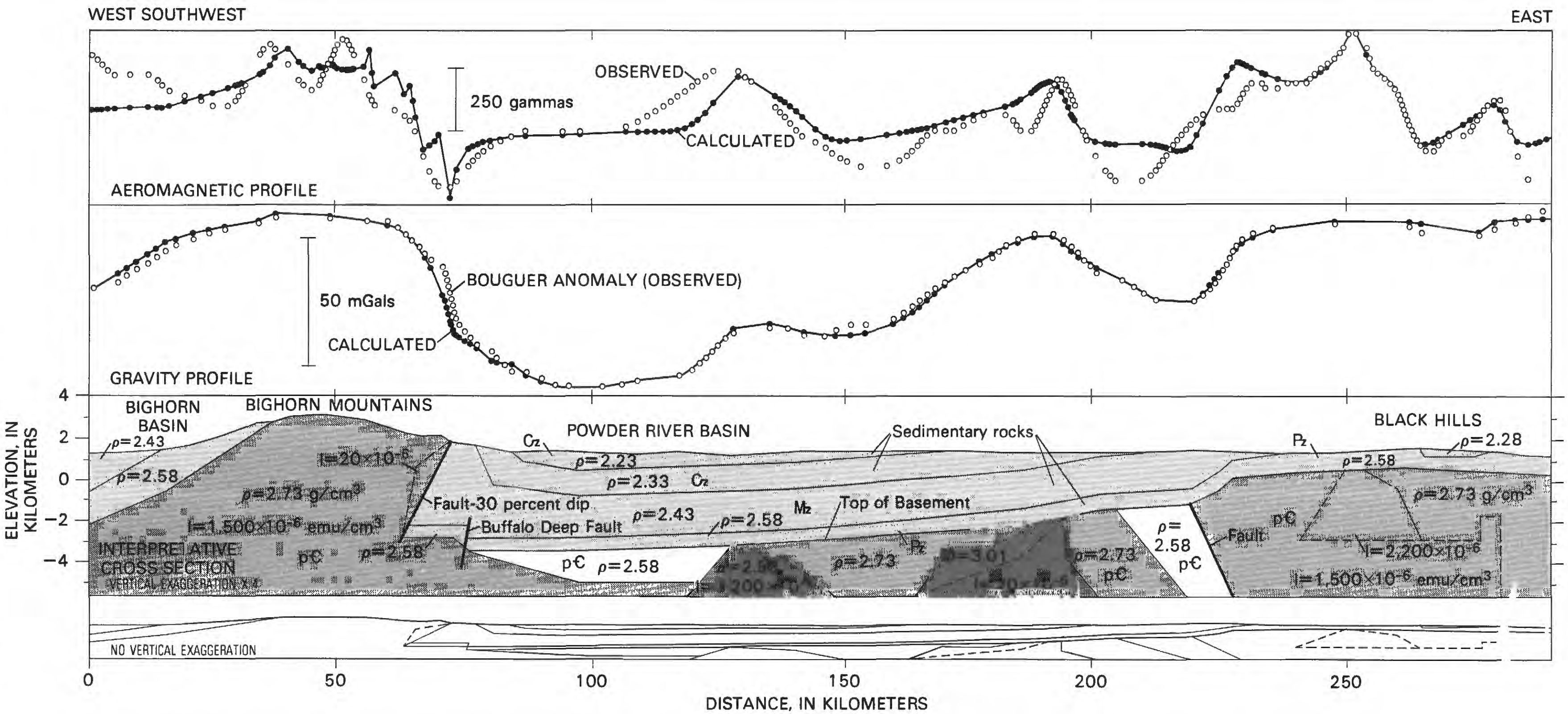

Figure 6. Gravity and magnetic profile across the Bighorn Mountains, central Powder River Basin, and Black Hills, including interpretative cross section that is shown at both 4 to 1 vertical exaggeration and 1 to 1. Location of profile shown in figure 1. Within the basement beneath the basin, both rock densities and rock magnetic susceptibilities are assumed, based on values measured within the Bighorn and Wind River Mountains. Therefore, the differences seen between the observed and calculated curves in both profiles is probably caused by greater heterogeneity within the basement rocks than we have assumed.

block (mostly in South Dakota) is structurally and topographically higher than the northwestern block (mostly in Wyoming) but is east of the study area.

DeWitt and others (1986) suggested that the Black Hills may be underlain by low-angle faults dipping to the east; especially the South Dakota block. Modeling of the gravity and magnetic anomalies (fig. 6) supports this concept for the Wyoming block of the Black Hills with a 45° east dipping thrust fault in the basement. The locations of the maximum gravity gradients on the HGA map (pl. 3) are over the Fanny Peak monocline. The exposed geology and topography of the area suggest that the upper limit of any unexposed fault traces would be west of the Fanny Peak monocline, thus supporting the concept of low-angle faults dipping to the east beneath the South Dakota block.

The aeromagnetic signature associated with the South Dakota block is predominantly a magnetic low with several local highs caused by small magnetic bodies within a non-magnetic Precambrian basement. The Wyoming block's signature is regionally higher and exhibits magnetic highs in the central part of the block that are probably associated with Eocene volcanics. The difference in the magnetic background levels between the two blocks suggests different basement provinces with the Wyoming block resting on a more magnetic crust that is more mafic and possibly older. The boundary between these two provinces may be a northeastward extension of the 1.6 Ma subduction zone proposed by Hills and Houston (1979).

Casper Arch

The Casper arch, located at the southwest corner of the PRB, is a structural saddle separating the Bighorn Mountains on the north and from the northern Laramie Range on the south; the PRB and the Wind River Basin lie to the east and west respectively (fig. 1). The arch is expressed in the gravity (pl. 2) as a saddle and in the magnetics as a broad low-amplitude north-south trending low (anomaly F). On the PRB side of the arch (east side), several small west-dipping reverse faults underlie an east-dipping section that steepens basinward (Moore, 1985). On the Wind River Basin side (west), however, the arch is separated from the Wind River Basin by a major east-dipping thrust. Ray and Berg (1985) used a northeast-southwest trending seismic profile to interpret this as a low-angle fault flattening to the northeast with at least 16 km of arch overhang above the basin sedimentary rocks. The HGA gravity map (pl. 3) also supports this interpretation with the maximum gravity gradient being on the east side of the fault's surface trace (fig. 2). Because the magnetic values across this arch show only very small highs at each edge of the arch, Precambrian basement involvement in this structure is possibly small.

Just northwest of the Casper arch (anomaly F), the aeromagnetic map (pl. 4) shows an east-west trending high (anomaly D) over the Owl Creek uplift indicating Precambrian basement involvement. Gravity modeling by Case and Keefer (1966) show this uplift to be bordered on the south by a high angle reverse fault, which the interpretation of the location of the gravity gradient on plate 3 also supports.

Northern Laramie Range

On plate 3, the northern end of the Laramie Range is shown to be separated from the PRB by a thrust fault (Blackstone, 1990). The gravity gradient anomalies in this area (pl. 3) do not clearly support this. However, the shape of the anomalies on the IRA (pl. 2) suggests a more complex system than just one thrust. The interpretation of the COCORP deep-seismic data farther south in the range (Brewer and others, 1982; Johnson and Smithson, 1985) also suggests a more complex thrust system than we see in the Bighorn Mountains, western Casper arch area (Ray and Berg, 1985), and the Wind River Mountains (Sharry and others, 1986).

The aeromagnetic values over this range (anomaly I) are not as high as over the Bighorn Mountains, suggesting a thinner wedge of Precambrian rocks, (which is compatible with the lower topography) or Precambrian rocks with a lower mafic content. A low-amplitude magnetic high (G) is present northeast of the Laramie Range (northeast of lat 43°N. and long 106°W.). This high is over the deepest part of the PRB and possibly represents a thick tongue of clastic material eroded from Archean basement rocks in the Laramie Range and redeposited within the basin sedimentary strata, or possibly a source within the basement similar to anomaly M.

Hartville Uplift

Similar to the northern Laramie Range-PRB boundary, the boundary between the Hartville uplift and the PRB is mapped as a southeast-dipping thrust fault (Blackstone, 1990) (pl. 3). Again, interpretation of the HGA map supports this. The IRA gravity map (pl. 2) shows this uplift to continue into the southeastern block of the Black Hills. The aeromagnetic high over the southwestern part of the uplift continues into the northern Laramie Range (anomaly H), suggesting a common origin. On the uplift, northeast of lat 42° 50′ N. and long 104° 15′ W., the magnetic high disappears. This suggests the presence of a Precambrian basement boundary, within the rocks of the present day uplift.

Porcupine Dome

This uplift (north of the PRB) is coincident with the east portions of both a large magnetic high anomaly (B, pl. 4) and a large gravity high (pl. 2) elongated in the east-west direction. The top of the dome basement is at a depth of less than 4,000 ft (1,200 m) below sea level (pl. 3), and the composition of the basement is unknown. The timing for the emplacement of the dome is also not known. The north side of the dome is separated from the rocks to the north by a left-lateral strike-slip fault (Cat Creek fault zone) (pl. 3). Because the HGA map shows a gravity gradient on the south side of the dome, it is reasonable to assume that there exists a major fault on the south side and that emplacement was during the Laramide orogeny. Brown and others (1984) believe that the Cat Creek fault zone is part of the Lewis and Clark lineament that is believed to be a Precambrian shear zone and that the dome is within the Central Montana uplift also believed to be Precambrian in age. Since the central part and highest values of the geophysical anomalies are to the west and not associated with the high part of the dome, this suggests that the composition of the dome is different than basement rocks north and south of the dome anomalies because these anomalies could not be caused by only the structure of the dome. This basement composition may be similar to the rocks that are causing anomalies M, N, O, P, and Q.

Hardin Platform

This area is of low structural relief with the Lake Basin strike-slip fault zone cutting through the area (pl. 3; Bergantino and Clark, 1985). The gravity signature (pl. 2) and to a lesser degree, the magnetic signature (pl. 4) of this area suggests that this is still part of the PRB with the PRB being separated from the Bull Mountains Basin by only a small unnamed arch.

Miles City Arch

This arch is a very long and broad (90–100 km) uplift that connects the Black Hills and the Porcupine dome. Very little is known about the basement composition. However, the variations in the geophysical anomalies suggests that the arch's basement has more than one lithology.

Anomaly Q appears to be a north extension of the northwestern block of the Black Hills. The magnetic signature (pl. 4) continues for about 80 km north of the Wyoming border; whereas, the gravity signature (pl. 2) dies out within 25 km of the border. This suggests that the broad magnetic anomalies to the north may be caused by buried Eocene igneous bodies similar to those found to the south in Wyoming.

Anomaly O is both a gravity and magnetic high (pls. 2 and 4) similar to the ones associated with the Wyoming block of the Black Hills, which suggests the existence of a third block of the Black Hills in Montana northwest of the Wyoming block.

The large magnetic anomalies at location P (pl. 4) are similar in magnitude, although of shorter wavelength, than the Porcupine dome anomaly. This suggests the possibility that the origin of these anomalies and others within the PRB including anomalies M and N is Precambrian in age with emplacement during the Laramide orogeny similar to Porcupine dome.

SUMMARY

Regionally, most of the area is composed of an Archean basement that may be among the oldest in the North American continent. In addition to evidence of this from outcrops and drillhole cores, a circular magnetic feature with elevated values is observed over much of Wyoming and southern Montana that is believed by some (Rush and others, 1983) to be a rough outline of the Wyoming Archean province. At the southeast and east edges of the Powder River Basin (PRB), an arc-shaped lower level background of magnetism is observed on the aeromagnetic map (pl. 4). It is quite possible that this lower level magnetic terrain is representative of Proterozoic or younger basement rocks. Within this younger basement is the southeastern (South Dakota) block of the Black Hills and the northeastern segment of the Hartville uplift.

High gravity values over the mountain ranges as seen on both the complete Bouguer anomaly (CBA) and the isostatic residual anomaly (IRA) maps (pls. 1 and 2) and a near-zero average for the IRA gravity values (pl. 2) indicate that these mountains are rootless and not in local isostatic equilibrium, but they are in regional equilibrium. Within the mapped area, all the ranges are seen as large gravity highs. This fact, along with the fact that the locations of the maximum horizontal gravity gradients associated with these highs are on the mountain side of the surface fault traces that separate the mountains from the basins (pl. 3), indicate that all these ranges were formed by low-angle thrusting. These faults also appear to flatten within the middle or lower crust (Robbins and Grow, 1992). Timing for the emplacement of the Bighorn Mountains and the Black Hills was during the Laramide orogeny probably in early Tertiary (DeWitt and others, 1986; Perry and others, 1992). Emplacement of the other mountains and uplifts in the study area was probably during this same period of time; although there is evidence for some uplift movement in these areas during the Paleozoic (Brown and others, 1984), thus suggesting that Laramide uplifts occurred in areas of previous structural highs. These other emplacements include the Porcupine dome, the Miles City arch, the Casper arch, the Hartville uplift, and the Laramie Range. The northern Laramie Range, although probably emplaced by thrusting, appears to have a more complex structure than some of the Laramide ranges to the north and west. The character of the magnetic highs associated with the above mountains and uplifts also suggests that the magnetic bodies causing these highs are shallow, which supports the idea of the low-angle thrust-block origin. Drillholes in the east edge of the Bighorn Mountains confirm that Precambrian rocks overlay PRB sedimentary rocks, and seismic interpretation in the same area (Robbins and Grow, 1992) show at least 6–11 km of offset.

The gravity lows are all associated with the foreland basins and are caused by low-density sedimentary rocks in the basin. Within the PRB, the gravity lows are lowest on the west side, conforming to the Basin's deepest areas and asymmetry. There are both gravity and magnetic highs that roughly coincide in location within the PRB (pls. 2 and 4). In fact, a few of the magnetic highs are larger than any over the mountains. These anomalies probably represent significant lateral density and magnetic differences with the basement rocks in the upper crust, which in turn are caused by major lateral lithologic differences. These differences are also seen in the Miles City arch.

The gravity and magnetic signatures over the Bighorn Mountains clearly show a distinction in the physical properties between the northern Archean granitic body (more dense and more magnetic) than the southern gneiss body. The gravity data also shows a contrast across an east-west trending line along the Crazy Woman Creek and Ten Sleep fault.

The Black Hills is known to consist of at least two separate blocks (the Wyoming and South Dakota blocks) (DeWitt and others, 1986). The Wyoming block differs from the South Dakota block in that there are Eocene volcanics in the area and it sits on Archean basement. The geophysical data suggests there may be a third block (in southeast Montana) to the northwest. The geophysical anomalies of the Wyoming and the proposed Montana blocks are similar but separate. However, the Montana block probably also sits on Archean basement with possible buried volcanics in the area.

Borehole gravity meter determined density measurements in six drillholes within and to the west of our study area show a decrease in density values to the east in sedimentary rocks of late Paleozoic and Mesozoic age that probably correlates with a decrease in overall deposit thickness and perhaps with facies changes.

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