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MAPS SHOWING GRAVITY AND AEROMAGNETIC ANOMALIES IN THE DILLON 1°×2° QUADRANGLE, IDAHO AND MONTANA

By

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CUSMAP

This report is one of a series of reports that present, chiefly with maps at a scale of 1:250,000 and 1:500,000, various aspects of the geology, geochemistry, geophysics, and mineral resources of the Dillon 1°×2° quadrangle, s uthwestern Montana and east-central Idaho. These studies were made largely under the Conterminous United States Mineral Assessment Program (CUSMAP), the primary purpose of which is to determine the mineral resource potential of selected 1°×2° quadrangles by means of a multidisciplinary approach. CUSMAP is intended to provide information on mineral resources to assist Federal, State, and local governments in formulating minerals policy and land-use policy and to produce sound scientific data that may be of value to private industry and the general public in mineral exploration and development.

INTRODUCTION

The Dillon 1°×2° quadrangle is characterized by gravity and magnetic anomalies that are useful for regional assessment of mineral resources. These anomalies, or perturbations of the Earth's gravity and magnetic fields, are caused by lateral variations in rock density and magnetization of the subsurface that provide clues about the compositions of buried lithologic units, configurations of basins and intrusive rocks at depth, and the geometry of hidden geologic structures. The geophysical information developed for the Dillon quadrangle extends similar studies by M.D. Kleinkopf, D.M. Kulik, and V.L. Bankey in the Wallace and Choteau 1°×2° quadrangles, Mont. (Kleinkopf, 1981; Kulik, 1983; Bankey and others, 1985; Kleinkopf and others, 1988); by D.R. Mabey and M.W. Webring (Mabey and Webring, 1985) in the Challis 1°×2° quadrangle, Idaho; and by W.F. Hanna, J.H. Hassemer, J.E. Elliott, C.A. Wallace, and S.L. Snyder in the Butte 1°×2° quadrangle, Montana (unpub. data, 1990). Geophysical maps of all of these investigators have contributed to geophysical compilations for the United States and North America (Kutina and Hildenbrand, 1987; Hinze and others, 1988; Hanna and others, 1989).

The geophysical data define anomalies a few square kilometers in area or larger. Thus, the scale of the investigations is commensurate with identification of broad geologic terranes favorable for mineral occurrence rather than locations of individual ore bodies. The approach to interpretation was to note correlations of anomalies or parts of anomalies with exposed rocks or mineral occurrences that were previously known; to determine or estimate, where feasible, the gross physical properties of these surficial anomaly-producing rocks; and to infer where similar anomaly-producing rocks may be present in the subsurface.

Gravity investigations included (1) the collection and measurement of selected rocks for bulk density; (2) the acquisition of new, and compilation of old, gravity-anomaly data; (3) editing and merging of gravity-anomaly data sets; (4) reduction of new data to complete Bouguer gravity anomalies (corrected for terrain); (5) reduction of all data to isostatic-residual-gravity anomalies; (6) development of derivative maps by computation of multiple directional derivatives, wavelength filtering, and analytical continuation; (7) development of a map showing the regional gravitational effect of a crustal root based upon an Airy-Heiskanen isostatic model; (8) modeling of selected anomaly sources; and (9) interpretative discussions of anomalies. Magnetic investigations included (1) measurements of remanent magnetization and apparent magnetic susceptibility of selected rock samples; (2) computations of total magnetizations of rock samples; (3) mosaicking of five existing aeromagnetic anomaly contour maps to produce a single map; (4) compilation of four sets of digital aeromagnetic-anomaly data; (5) digitization of one analog data set along flight lines and subsequent removal of an appropriate International Geomagnetic Reference Field (IGRF); (6) computer merging of data sets, gridded at 0.75-km and 1.5-km intervals, to produce single-datum anomaly maps, one corresponding to each grid; (7) development of derivative maps, including reduced-to-pole (north) maps, pseudogravity maps, magnitude of horizontal gradient of pseudogravity, machine-generated crests of the maxima of these horizontal gradients, second vertical derivative of the single-datum and reduced-to-pole maps, and a map showing probable occurrences of significant amounts of subsurface magnetic rocks, mainly plutonic and metamorphic rocks; (8) modeling of selected anomaly sources; and (9) interpretative discussions of anomalies. Some of the derivative maps of both gravity and magnetic anomaly data are shown as principal maps or figures in this report.

GEOLOGIC SETTING

The Dillon quadrangle occupies a part of the Rocky Mountain overthrust belt characterized by northerly trending mountain ranges and adjoining intermontane basins (map A). The quadrangle is transected principally by the Grasshopper thrust plate (index map), which is fringed on the east by a frontal zone of complex folding and terminal thrusting showing eastward movement against crystalline rocks of the craton that are present near the eastern margin of the quadrangle (Ruppel and others, 1981; Ruppel, 1982; Ruppel and others, 1993).

The cratonic rocks east of the thrust belt consist of Paleozoic and Mesozoic sedimentary rocks about 3.5 km thick that overlie Archean crystalline rocks. The frontal fold and thrust zone includes most of the formations of the craton-shelf sequence, which here change abruptly in lithology, thickness, and stratigraphic sequence and are tightly folded, overturned in places, and cut by many imbricate thrust faults. The Grasshopper plate consists of a thick section of Proterozoic sedimentary rocks overlain by a thin section of Paleozoic sedimentary rocks that moved laterally along an east-west fault of the Horse Prairie fault zone just south of the quadrangle. Autochthonous rocks are restricted principally to the Proterozoic Yellowjacket Formation in the southwestern corner of the quadrangle (Ruppel and others, 1993).

Thrusting appears to have ceased just prior to major emplacements of plutonic and volcanic rocks, including plutons of the Pioneer, Boulder, Tobacco Root, and Sapphire batholiths. Following intrusion, the region was subjected to deformation that produced steeply inclined faults (Suttner and others, 1972, 1981; Brumbaugh, 1973; Schmidt and others, 1977; Reynolds, 1979; Ruppel, 1982; Ruppel and Lopez, 1984), traditionally inferred to be normal faults near the margins of mountain uplifts, such as in the Basin and Range province south of the study area, but alternatively inferred to be strike-slip faults that overstep one another to form pull-apart basins (Ruppel, 1991).

Much of the quadrangle is extensively mineralized (McClernan, 1975; Klepper and others, 1977). A list of known mineral deposits within the quadrangle, containing more than 800 mines, deposits, and mineral occurrences, was compiled by mining district or area (Loen and Pearson, 1984), including descriptions of local geologic environments. Most of the known deposits, such as vein and replacement deposits, are spatially related to igneous intrusive rocks; others, such as bedded iron-formation and podiform chomite, occur in metamorphic rocks. Because of these spatial-lithologic affinities, magnetic and gravity data marking subsurface igneous intrusive rocks and anomalous bodies in metamorphic rock are of special interest in this report.

The diverse rock types represented in the quadrangle are characterized by a broad spectrum of rock density and magnetization. Data representing 291 rock samples are summarized in table 1; most sampling sites are shown on map A. Density values are largely commensurate with those measured by Davis and others (1965a,b), Burfeind (1967, 1969), Biehler and Bonini (1969), and Smith (1970). To a first approximation, dry bulk densities of Archean rocks average about 2.85 g/cm^3; Proterozoic, Paleozoic, and Mesozoic sedimentary rocks, 2.70 g/cm^3; volcanic rocks, 2.65 g/cm^3; and plutonic rocks, 2.67 g/cm^3. Basin-fill deposits, though highly variable in composition, may have an average density of about 2.25 g/cm^3, as obtained by Vijay Satoskar of Indiana University (Burfeind, 1967, p. 18), using Nettleton's (1939) density profiling method over Oligocene basins. Wet bulk density measured for a limited number of samples is on the average only about 0.01–0.02 g/cm^3 higher than the corresponding dry bulk density.

Magnetization of rock samples, derived by measuring remanent magnetization and magnetic susceptibility, has a range of about five orders of magnitude. Anisotropy of magnetization, which in an extreme form can significantly affect both induced and remanent magnetization (see, for example, Hanna, 1977b), is detectable in foliated, amphibolite-rich metamorphic rocks, such as some described by Burger (1966), but strong only in banded iron-formation, which is not abundant. Therefore, effects of this anisotropy are neglected in discussions of anomalies. In general, total magnetization that causes anomalies has normal polarity in a direction that differs about 15° or less from the direction of the present geomagnetic field. As exceptions, parts of two plutons in the quadrangle are magnetized in intermediate directions and part of one pluton has a reversed polarity. A few intermediate directions of volcanic rocks are inconsequential with regard to analysis of anomalies because of their weak intensities.

Rocks having extremely strong magnetization of more than 100 amperes per meter (A/m) are limited to Archean iron-formation. Those having strong magnetization of 1–10 A/m include most plutonic rocks and some, but not all, volcanic rocks and Archean amphibolite, amphibolite gneiss, ultramafic rock, metamorphosed diabase, and lamprophyre. Others having weak magnetizations of about 0.1 A/m include a few Cretaceous and Tertiary plutonic and volcanic rocks and some occurrences of Proterozoic sedimentary rocks. Relatively nonmagnetic rocks having magnetization of less than 0.1 A/m include most Archean gneiss, schist, and marble; Proterozoic, Paleozoic, and Mesozoic sedimentary rocks; and Tertiary and Quaternary basin fill and surficial deposits. Some exceptions to the above generalizations may be noted in table 1.

GRAVITY ANOMALY DATA

The heart of the data base for the Dillon quadrangle consists of approximately 2,050 gravity observations made by H.E. Kaufmann, S.B. Sorensen, and K.J. O'Neill (Kaufmann and Hanna, 1982; Kaufmann and others, 1983). These data were supplemented by a few hundred additional observations made by J.H. Hassemer in the Farlin Creek, Ruby Mountains, and Blacktail Mountains Wilderness Study Areas and in the southern Highland Mountains (Hassemer and others, 1986) and by B.D. Ruppel throughout the Big Hole Basin. These U.S. Geological Survey data were obtained by field vehicle, helicopter, animal pack train, or on foot by means of LaCoste and Romberg geodetic gravimeters. All measurements are referenced to gravity measured at a base station in Dillon, Mont. (Kaufmann and others, 1983), incorporated into the International Gravity Standardization Net 1971 (Morelli and others, 1974; U.S. Defense Mapping Agency Aerospace Center, 1974).

Observed gravity was computed according to calibration coefficients established by laboratory bench and mountain loop calibrations, and a computer program developed by M.W. Webring, R.R. Wahl, and G.I. Evenden was used to correct for earth tide and instrumental drift. Bouguer gravity anomalies corrected for terrain and earth curvature, assuming a reduction density of 2.67 g/cm^3, were computed relative to theoretical gravity values derived for the Geodetic Reference System 1967 (International Association of Geodesy, 1971; Woollard, 1979). Equations used in this gravity reduction are summarized in Cordell and others (1982) and are implemented in a computer program of R.H. Godson. Terrain corrections to a distance of 53 m (Hammer, 1939) from each measurement point (station) were visually estimated during the field work from topographic approximations for inclined planes (Sandberg, 1958), conal surfaces, and two-dimensional irregular forms (Hubbert, 1948). Terrain corrections beyond 53 m, extending to a distance of 166.7 km from each station, were computed according to a modification of the method of Plouff (1977) and incorporating U.S. Department of Defense terrain data digitized at a 15-second grid interval. For purposes of editing and display, the latitude and longitude of gravity stations were projected to x,y coordinates at a scale of 1:250,000 according to a Universal Transverse Mercator transformation. Bouguer gravity anomaly values corresponding to these points were gridded by means of a minimum curvature algorithm (Briggs, 1974; Webring, 1981). The gridded anomaly data were subsequently contoured by means of an algorithm for splining under tension (Cline, 1974; Evenden, 1975; Godson and Webring, 1982) and were machine plotted (map B). The U.S. Geological Survey data, after contour plotting, were compared to edited and partially field-checked data of Burfeind (1967), to regional data of Biehler and Bonini (1969), and to a few data of the U.S Department of Defense Gravity Library (Hittelman and others, 1982).

Because deep roots of crustal layers may isostatically compensate for the mass effects of topographically elevated areas, the effect of such compensation on the Bouguer gravity anomaly in mountainous regions may be significant. The effect may be estimated by computing the gravitational attraction of an assumed compensating root (fig. 1); this computed attraction may be subtracted from the Bouguer gravity anomaly to obtain an isostatic residual gravity map that delineates anomaly sources in the shallow crust. Such an isostatic residual gravity map (fig. 2) was prepared by the technique of Simpson and others (1983a), based on an Airy-Heiskanen model (Heiskanen and Moritz, 1967) of local compensation. Compensation of the surface load was based on a 30-second gridded topographic data set. The parameters chosen for the model are those used by Simpson and others (1985), consistent with Woollard's (1968) best fit of seismic refraction depths to the Mohorovicic discontinuity beneath the United States: a depth to the bottom of the root of 30 km for sea-level elevations, a density contrast at depth of 0.35 g/cm^3, and a surface load density of 2.67 g/cm^3. The gravitational attraction of the compensating deep root (fig. 1), computed at sea level to a radial distance of 166.7 km by the technique of Simpson, Jachens, and Blakely (1983) and computed beyond this radial distance to the antipode of each gravity station according to data of Karki and others (1961), has a range of values of about 28 mGal in the quadrangle. The anomalous features are long in wavelength and, to a first approximation, represent a regional field having geological and topographical parameters, as an alternative to a visually estimated regional field or a regional field estimated by mathematical filtering. A broad nose just west of center on the map (fig. 1) partly reflects the influence of subsurface masses assumed to compensate for the Big Hole basin.

Because the compensating root is so broad relative to the dimensions of the quadrangle, its long-wavelength gravitational field guarantees that the local features of the isostatic residual anomaly map will look very similar to the local features of the Bouguer gravity anomaly map. For convenience, and in conformity with conventional analyses of areas the size of the Dillon quadrangle, we arbitrarily use the Bouguer gravity anomaly map (map B) for further discussion of anomalies. The isostatic residual anomaly map (fig. 2) can continue to serve as a small-scale rendition of the gravity anomaly map.

MAGNETIC ANOMALY DATA

Total-intensity aeromagnetic anomaly data for the quadrangle are based mainly on six surveys (surveys A–F, indexed on map C) flown at different times and having different specifications (Johnson and others, 1965; Zietz and others, 1971; U.S. Geological Survey, 1975, 1979, 1981a,b). In about 60 percent of the quadrangle flightlines were spaced 3 km apart; in the remaining 40 percent (except for a narrow rectangle of regional data in the northwestern corner of the quadrangle) flightlines were spaced 0.8 km apart. A mosaic map of these surveys, derived photographically and showing discontinuous contour lines along borders, was released as a 35-mm slide by Kaufmann and Hanna (1982).

For purposes of the present study, a single-datum magnetic anomaly map (map C) was created by mathematically merging the six diverse data sets to simulate a single survey flown 3.2 km above mean sea level. Such a synthesized map, while lacking details preserved in the original data, permits projection of anomalies and high-gradient zones across individual map boundaries and permits comparison of anomaly amplitudes as they relate to inferred magnitudes of total magnetizations of source rocks and topographic effects of source rocks. Such a single-datum map also provides a basis for generating filter and other derivative maps that are useful for outlining boundaries of magnetic source rocks in the subsurface (see, for example, Cordell and Grauch, 1982). This single-datum map, when compared to the reconnaissance map (Geodata International, Inc., 1979) developed in conjunction with the National Uranium Resource Evaluation program, provides a greater amount of regional information for the purpose of interpreting gross lithologies and structures.

The single-datum map (map C) was produced by first manually digitizing the analog data of each of the surveys along contour lines. The resulting points were then projected, gridded, and contoured. Data of surveys C, D, and E were then continued upward and data of survey B continued downward to the 3.2-km level of survey A, by means of computer programs of Hildenbrand (1983) and Grauch (1984). The continued data were then merged by splining techniques developed by B.K. Bhattacharyya, R.E. Sweeney, R.H. Godson, T.G. Hildenbrand, M.W. Webring, and J.D. Phillips (see, for example, Bhattacharyya and others, 1979; Phillips and Hildenbrand, 1981; Hildenbrand and others, 1982). Following this merging, the data were further integrated with a 15-minute "picture frame" of similarly gridded data digitized from Zietz and others (1980) and Bankey and others (1985). The resulting data set, gridded at both 0.75- and 1.5-km intervals, was reduced to the pole in order to position anomalies better directly over source rocks, assuming no anomalously directed rock magnetization. This reduced-to-pole anomaly map is shown at small scale in figure 3.

INTERPRETATION OF GRAVITY ANOMALIES

The Bouguer gravity anomaly map is characterized by negative values that are part of a vast circular low about 300 km in diameter that is associated largely with the Idaho batholith (Eaton and others, 1978; Bankey and others, 1985; Bankey and Kleinkopf, 1988; Cady and others, 1990). Superposed on this extremely long-wavelength low are regional lows that are associated with basins and batholiths and highs that are associated with terranes of high-grade metamorphic rocks.

The Bouguer gravity anomaly map (map B) thus shows strong correlations with exposed Tertiary basin fill and Quaternary surficial deposits, Cretaceous plutonic and volcanic rocks, and Archean metamorphic rocks. Some anomalies that extend beyond the limits of exposed bedrock clearly point to subsurface extensions of these rocks. Other anomalies that tend to align or cluster imply subsurface structure. As an aid to the reader, some of the more prominent or geologically significant anomalies are labeled on map B (G1–G52). Gravity features associated with valleys or intermontane basins are discussed first, followed by comments on features associated with more elevated terranes of bedrock.

GRAVITY FEATURES OF VALLEYS AND INTERMONTANE BASINS

The 30- to 40-mGal low (G1–G5) that dominates the western half of the quadrangle is associated with low-density basin fill and surficial deposits of the Big Hole basin, the largest and deepest intermontane basin of the quadrangle and of southwestern Montana. The deepest part of this prominent basin, whose gravity signature is evident even on small-scale maps of the conterminous United States (Society of Exploration Geophysicists, 1982; Simpson, Saltus and others, 1983), is about 3 km southwest of Wisdom, in a region bounded by the –250-mGal contour line. The maximum depth of the Big Hole basin, assuming a lateral density contrast between basin fill and country rock of 0.45 g/cm^3 and using computer programs modified from those of Cordell (1970), Cordell and Henderson (1968) and Bott (1973), is estimated to be about 5.0 km (recognizing that the single density contrast assumed is simplistic with regard to the diversity of rock types in the subsurface and to unknown horizontal and vertical variations of basin-fill density). Thicknesses of basin fill centered near anomalies G2 and G3 are estimated to be about 3.0–3.5 km, respectively. The great thickness (5.0 km) at anomaly G4 continues, decreasing only slightly, at least 10 km southward, as outlined by the –248 mGal contour line. Thickness of basin fill diminishes abruptly a few kilometers farther south, near lat 45°15′ N., probably delineating an east-west fault, as shown by Ruppel and others (1981).

The steep gradients flanking the gravity low, as much as 10 mGal/km in places, are characteristic signatures of high-angle boundaries that extend into the subsurface and separate materials of high contrast in density. These high-angle boundaries may be nearly vertical faults, such as normal or strike-slip faults, extending to great depth; however, the gravity data alone do not preclude the possibility that these faults are very steep at shallow depth but are more shallowly inclined at greater depth. In general, on the basis of gravity modeling alone, it is difficult to distinguish unequivocally a deeply extending, nearly vertical fault from a listric fault that is associated with the collapse of valley fill because both structures have similar geometry at shallow depth where the gravitational attraction predominates. Rather, discrimination of these structures may ultimately require a combination of refraction and reflection seismic data, borehole gravimetry to determine deep patterns of rock density, and deep drilling. Other steep gravity gradients that imply subsurface structures include the northwest flank of the anomaly extending from G1 to G3, which marks a northeast-trending fault, and the flank from G4 to G5, which marks a north-northwest-trending fault. The eastern flank of the anomaly delineates a fault zone that is steeply inclined or vertical at least to moderate depths and that is subparallel to the fault zone beneath the western flank. The pair of faults clearly bound a down-dropped block now filled with basin and surficial deposits (Ruppel and others, 1981) or, alternatively, a pull-apart basin (Ruppel, 1991).

Southeastward from the gravity low of the Big Hole basin, weaker lows G6 and G7 are underlain by basin and surficial deposits estimated to be about 0.5 and 2.0 km thick, respectively. Much more prominent in amplitude, low G8, about 12 km to the east, appears to represent a relatively narrow subsurface depression flanked by nearly vertical faults and filled with valley deposits estimated to be as thick as 3.5 km in an area 8 km south-southwest of Polaris and as thick as 4.0 km in an area 8 km farther south. The northern extremity of the subsurface depression coincides approximately with the southern terminus of the Pioneer batholith. Southwestward, this gravity low continues vaguely to low G9, associated in part with sediments of the western extremity of Horse Prairie valley. It is noteworthy that most of Horse Prairie valley is characterized by a flat anomaly field; sediments beneath the valley are inferred to be relatively thin.

Near Salmon, Idaho, lows G10 and G11 are associated with sediments of the Lemhi Valley and Salmon River valley. Basin fill and surficial deposits are inferred to be moderately thick, reaching a maximum of perhaps 2.5 km in a region 5 km east of Salmon. Steep gradients along the western and northeastern flanks of the low, extending from G10 to G11, mark locations of possible subsurface boundaries that are high angle to at least a moderate depth.

The eastern part of the quadrangle is also traversed by a prominent north- to northeast-trending gravity low covering the Jefferson River valley in the northeastern part of the quadrangle and the northwest flank of the Ruby Range farther south. Northwest-trending lows branch from this larger low in the lower Ruby River valley south of Sheridan and in the Blacktail Deer Creek valley south of Dillon. The Beaverhead River valley, which, like the Jefferson River valley, Ruby River valley, and region near Blacktail Deer Creek, has extensive mapped basin fill and surficial deposits, is associated with a gravity high rather than with a low and is the only major valley in the quadrangle not associated with a gravity low. Low G12 implies a maximum basin-fill thickness of about 1.5 km in a region halfway between Whitehall and Twin Bridges; low G13 implies a maximum thickness of 1.0–1.5 km about 12 km south of Twin Bridges, both estimates based upon an assumed average density contrast of 0.60 g/cm^3. The assumed density contrast, however, may be too large because analyses of seismic data (Brunsvold, 1989; Hanneman, 1989) imply depths of as much as 3.5 km. The eastern flank of G12 and both the eastern and western flanks of G13 mark high-angle subsurface faults bounding subsurface depressions. Southwest of low G13, about 12 km east of Dillon, low G14, in the shape of a local gravity dish, reflects a local thickening of basin deposits of 1 km or more. If shown at a very large scale, this anomaly, controlled by several dozens of points too closely spaced to plot on the regional map, is elongate northeastward, the southeastern flank coinciding with a mapped fault. This southeastern flank contains the steepest gravity anomaly gradient of the quadrangle, nearly 15 mGal/km. Farther southwest, low G15 of the Blacktail Deer Creek region suggests a basin-fill thickness of about 0.5–1.0 km. The southwestern flank of this low tapers to a narrow elongate low to the southeast and is aligned with low G16 to the northwest. The southwestern flank of G15 and its tapered extension coincide with a mapped fault (Ruppel and others, 1993) southwest of Blacktail Deer Creek. Low G16 is broader and presumably reflects a combination of underlying basin fill and volcanic rocks. Near the southeastern corner of the quadrangle, local low G17 has a steep southwestern flank, which merges northwestward into a similar flank projecting from low G13, both aligned with a northwest-trending fault of this part of the Ruby River valley near Alder. Regional low G18, in the extreme southeast corner of the quadrangle and extending southward across the quadrangle boundary, reflects a very thick accumulation of basin fill, perhaps as much as 5.0 km, in this part of the Ruby River valley. The western flank of this anomaly marks a north-trending, high-angle subsurface fault; the eastern flank nearly coincides with a succession of connected mapped faults (Ruppel and others, 1981). Immediately south of this region, a major listric fault has been postulated on the basis of gravity modeling and drill-hole data (Kulik and others, 1985; Kulik and Perry, 1988). Near here, other structural features have been inferred by Schofield (1981) on the basis of gravity modeling of basin fill and igneous rocks.

GRAVITY FEATURES OF ELEVATED TERRANES OF COUNTRY ROCK

A number of low-amplitude, short-wavelength gravity anomalies in the northwestern part of the quadrangle are associated with a terrane of sedimentary and plutonic rocks. Local high G19, as well as unlabeled lower-amplitude local highs within 25 km to the northeast and southwest, are characteristic of the mixed terrane of diverse plutonic rocks of the Bitterroot lobe of the Idaho batholith (Elliott and others, 1983), Challis Volcanics, and Proterozoic sedimentary rocks of the Belt Supergroup. These low-relief anomalies are caused by subtle variations in subsurface rock densities. More regional, moderately high amplitude highs G25–G32 in the southwestern part of the quadrangle are characteristic of sedimentary rocks of the Precambrian Yellowjacket Formation and Proterozoic and other sedimentary rocks of the Grasshopper Thrust Plate (Ruppel and others, 1981). Similarly, in the central Pioneer Mountains low-amplitude lows G33–G35 reflect subtle variations of subsurface densities of various plutonic rocks and Proterozoic rocks in this thrust plate (Berger and others, 1983; Pearson and others, 1987). These patterns of low-amplitude anomalies, both lows and highs, prevail along the eastern and northeastern margins of the Pioneer Mountains, taking the form of lobes developed especially along the –220-mGal and –200-mGal contour lines. Some of the local highs formed by the westward- and southwestward-pointing lobes of these contour lines (for example, those within 15 km of high G36) are associated largely with plutons that are probably satellitic intrusions of the Boulder or Pioneer batholith. High G37 is a higher-amplitude feature associated with parts of such intrusive bodies. High G38, clearly associated with the Mount Fleecer stock, contrasts strikingly with low G39 only 6 km farther east, which is associated with much of the Moose Creek stock (Andretta, 1961; Smedes and others, 1980). This contrast between a gravity high and a low is not caused by sharp differences in the densities of the stocks or in the depth of their roots, but by the differing densities of the country rocks that they intrude. In this case, the Mount Fleecer stock intrudes Paleozoic and Mesozoic sedimentary rocks of average lower density than that of the largely Archean metamorphic rocks that the Moose Creek stock intrudes. The density contrast between Boulder batholith and Archean metamorphic rocks at depth is vividly shown by the broad low extending about 20 km southwest and west from Butte, local low G40 being further affected by the presence of lower-density basin-fill deposits. Gradients flanking low G41, which is associated with much of the Hell Canyon pluton, suggest that this pluton is connected to the Boulder batholith proper at depth, just as is the case for low G39 of the Moose Creek pluton. The gravity data, however, do not indicate necessarily that the Mount Fleecer stock is connected to the batholith proper at depth. Low G42, centered near Whitehall, in the northeastern corner of the quadrangle, is another extension of the Boulder Batholith low, probably caused by a combination of volcanic and possibly unknown plutonic rocks, basin-fill deposits, and surficial deposits.

Like the Boulder batholith, the smaller Tobacco Root batholith, whose westward exposed extremity is about 25 km east of Twin Bridges at the eastern edge of the quadrangle, is characterized by the flank of a conspicuous gravity low, G43. The steep gradients of flanks of this anomaly, mapped east of the quadrangle by Burfeind (1967), reflect the large density contrast between batholith rocks and high-density Archean metamorphic rocks in the subsurface. These Archean rocks are characterized by gravity highs, such as G44, 15 km east of Silver Star (Abdul-Malik, 1977); G45, 10 km southeast of Sheridan; and the broad high of the Ruby Range (Tysdal and others, 1987b), punctuated by local highs such as G46 and G47.

One of the most remarkable features of the gravity anomaly map is the regional high outlined by the –180-mGal contour line extending from a region about 10 km east of Melrose southward to Dillon, including highs G48 and G49. This high is associated with a vast region of mapped low-density basin-fill and surficial deposits, many of which are in the Beaverhead River valley. The high is undoubtedly caused by relatively shallow, high-density Archean metamorphic rocks, the –190-mGal contour line crudely outlining most of the exposed and buried Archean rocks in the southeastern part of the quadrangle. Thus, the gravity anomaly map shows that Archean rocks of the Ruby Range extend continuously at depth to those exposed in the Highland Mountains (Duncan, 1976). Likewise, the anomaly saddles between G13 and G17 and between G12 and G13 indicate that the Archean metamorphic rock terranes of the Ruby Mountains and Highland Mountains are connected to similar Archean terrane of the Tobacco Root Mountains. Highs G50, G51 (Tysdal and others, 1987a), and G52 are further evidence that Archean rocks underlie volcanic and sedimentary rocks immediately west of Dillon and in the drainage area of the Beaverhead River 15–30 km southwest of Dillon.

Profiles of closely spaced gravity observations within a few kilometers north of G48 (J.M. O'Neill, oral commun., 1986) and a few kilometers west-southwest of G48 (C.J. Wideman, Montana College of Mineral Science and Technology, oral commun., 1986) are being used for interpretations of the structural relationships between Archean and Proterozoic rocks near the Camp Creek fault zone and the structural configuration of a graben east of the McCartney Mountain stock (Chandler, 1973).

INTERPRETATION OF MAGNETIC ANOMALIES

The single-datum (map C) or reduced-to-pole (fig. 3) magnetic anomaly map can be used to discriminate readily strongly magnetized regions from weakly magnetized regions in an approximate way. For example, the 100-nT contour of the reduced-to-pole anomaly map delineates most of the mapped magnetic rocks. Even less strongly magnetized regions, such as those lying between the 0- and 100-nT contours, signal the possibility of subsurface magnetic terrane. By observing amplitudes and polarities of anomalies region by region, one can deduce generally that (1) plutonic rocks of the Bitterroot lobe of the Idaho batholith in the northwest corner of the quadrangle appear to be less strongly magnetic than compositionally similar plutonic rocks of the Boulder batholith, Pioneer batholith, and Tobacco Root batholith in the eastern two-thirds of the quadrangle, although some anomalies are strongly affected by topography (proximity of magnetic terrain to the magnetometer sensor); (2) younger plutonic rocks, such as biotitic granodiorite and granite about 68–73 Ma (unit Kbgg on maps B and C) are less highly magnetic than older plutonic rocks, such as granodiorite, quartz diorite, and tonalite, that contain biotite and hornblende and are about 73–79 Ma (unit Kghb on maps B and C); (3) a prominent swath of buried magnetic terrane, presumably plutonic rocks, trends diagonally across the western third of the quadrangle, from the northwest corner of the quadrangle and southeastward across the southern part of the Big Hole basin; and (4) part of the magnetic metamorphic rock terrane of the Ruby Range extends northwestward beneath the southern part of the Beaverhead River valley near Dillon, but most of the buried metamorphic rock terrane indicated by gravity anomaly data is relatively nonmagnetic.

The magnetic anomaly data also may be transformed to a pseudogravity anomaly map (fig. 4) by use of Poisson's relation. This transformation has three purposes: (1) It shifts anomaly centers directly over their sources, effectively correcting for the magnetic inclination of the Earth's magnetic field, just as does the reduced-to-pole anomaly map; (2) unlike the reduced-to-pole transformation, it converts magnetic anomalies to gravity anomalies on the assumptions that sources generate both types of anomalies and that the average ratio of density to magnetization is known (thus, locations of pseudogravity anomalies can be compared directly with locations of measured gravity anomalies to determine which sources actually generate both types of anomalies); and (3) it offers a mathematically noise-reduced function from which magnitudes of horizontal gradients can be computed (fig. 5), thereby highlighting narrow regions where sources have steep boundaries in the shallow subsurface. Comparison of the pseudogravity anomaly map (fig. 4) with the gravity anomaly map (fig. 2) at a common scale shows that sources of both types of anomalies include parts of the Tobacco Root, Boulder, and Pioneer batholiths and parts of the high-grade metamorphic terrane in or near the Ruby Range. The map showing horizontal gradients of pseudogravity anomalies (fig. 5) was contoured (at the sacrifice of some clarity of labeling) at an interval that clearly delineates by closely spaced contours those zones at the peripheries of magnetic bodies where source boundaries are steepest in the shallow subsurface.

In the discussions of magnetic anomalies that follow (map C), anomalies inferred to be caused by plutonic rocks are discussed first and those caused by metamorphic rock second.

ANOMALIES ASSOCIATED WITH PLUTONIC ROCKS

In the northwest corner of the quadrangle, northwest of the Big Hole basin, plutonic rocks of the Bitterroot lobe of the Idaho batholith are characterized by numerous short-wavelength anomalies that are generally larger in amplitude over older Cretaceous plutons (unit Kghb) than over Younger Cretaceous plutons (unit Kbgg). Samples of quartz monzonite and granodiorite from exposures of the younger rocks (for example, samples 39 and 42, table 1) are only weakly magnetic; a sample of granodiorite from an exposure of the older rock (sample 40, table 1) is strongly magnetic. Although most of the anomalies in this region are associated with exposed plutonic rocks, others, like M1, are caused by buried plutons intruded into Proterozoic sedimentary rocks at shallow depth. Local high M2, at the north edge of the quadrangle, is a good example of an anomaly associated with known mineral occurrences (Elliott and others, 1983) on its flanks, an association noted previously in areas northeast of the quadrangle (see, for example, Hanna, 1978). The anomaly immediately north of M1 is the southern terminus of a conspicuous zoned high associated with the Sapphire batholith, north of the Dillon quadrangle (Hassemer and Hanna, 1982; Wallace and others, 1983).

The anomalies associated with rocks of the Idaho batholith broaden to the south, partly because of an increased flight altitude of the magnetometer sensor. However, these anomalies are just as complex as those to the north, as shown by high M3, centered over the southernmost extremity of exposed rocks of the Joseph pluton. About 20 km south of M3, approximately at M4, a pair of highs reflects two of several buried plutons along the Beaverhead Mountains and southwestern margin of the Big Hole basin, marked by M5–M9. Within this belt of anomalies, M7 appears to be caused in part by the exposed Carmen stock, and it is possible that M6 is caused by a more magnetic, large apophysis of this stock extending east and southeast in the subsurface from the exposed plutonic rocks. The magnetic low in the extreme southwestern corner of the quadrangle is a reflection of the relatively nonmagnetic character of the Challis Volcanics and associated basin-fill deposits, rather than an expression of reversed total magnetization.

In contrast to anomalies in the western third of the quadrangle, many of those in the eastern two-thirds are areally broad and very high in amplitude. For example, the belt of isolated buried plutons marked by M4–M9 merges eastward and is perhaps continuous with a large, completely buried body that is the western and northern subsurface extension of the exposed Bloody Dick stock. This plutonic body, if completely exposed, would be of batholithic size. The buried massif generates high M10, and its northernmost apophysis is marked by lobe M11.

About 35 km north of the Bloody Dick stock high, a high-amplitude magnetic high, M12, reflects the westernmost subsurface occurrence of plutonic rocks belonging to the Pioneer batholith (Zen and others, 1975, 1979, 1980; Pearson and Berger, 1980; Berger and others, 1981; Snee, 1982). This high, like M10, is associated with a mapped intrusive body, the Francis Creek pluton (Snee, 1982), that extends westward beneath basin-fill and surficial deposits along the margin of the Big Hole basin. This anomaly extends almost continuously northward to high M13, associated with a combination of older and younger plutonic rocks, where it abruptly bends southeastward, not continuing northward across younger plutonic rocks of the Doolittle Creek pluton. This southeastward protrusion is marked by high-amplitude magnetic highs M14, M15 (with elongate extension M16), and isolated M17 6 km to the north, all associated with older plutonic rocks. The vast tract of younger plutonic rocks extending northward for 25 km from M13 and the tract contained within the region central to M14–M17 are largely associated with low-amplitude lows, indicating that these rocks are weakly magnetic, in general agreement with sample measurements of table 1.

Although subdued, high M17 appears to continue northeastward, where it connects to the most prominent magnetic high (composed of local highs M18–M29) of the quadrangle, which is associated with topographically high plutonic rocks of the eastern and central Pioneer Mountains. This prominent regional high, which has a distorted annular or horseshoe shape, conforms approximately to the subcircular map distribution of high peaks of the mountains. As viewed on the reduced-to-pole map, the numerous local highs are associated with numerous plutons of various compositions (Berger and others, 1983; Pearson and others, 1983) and diverse magnetic properties (table 1). Gradients are steepest on the flanks of M22 and M27 at the southeasternmost and southwesternmost extremities of the batholith, respectively. Gradients of M22 may be partly attributable to magnetite-rich skarn in Paleozoic rocks (Collins, 1977), some of which was probably mined for local smelter flux in the Birch Creek mining district (Loen and Pearson, 1984). Although occurrences of skarn magnetite deposits have not been reported at M27 in the Baldy Mountain mining district, the similar high magnetic gradients and geologic setting suggest that such deposits could be present. Between highs M26 and M27, which are associated with gabbro, an elongate magnetic low coincides partly with a gravity low along Farlin Creek, suggesting subsurface alteration of plutonic rocks. Just east of this area audio-magnetotelluric and telluric measurements (Hoover and Pierce, 1984) indicate a subsurface zone of low-resistivity fractured and altered granodiorite, having resistivities similar to those observed at a molybdenum-bearing mineralized zone about 10 km to the north.

Throughout the Pioneer batholith region, known mineral occurrences are commonly associated with either the middle to upper flanks of magnetic highs that are not attributed to magnetic topography and that presumably mark steep contacts of buried plutons, or they are associated with magnetic lows presumably marking hydrothermally altered rocks. One high of special interest has the form of a nose that extends northwestward from M20. This high traverses the Hecla mining district and indicates that the mineralized sedimentary rocks of the district are underlain by an apophysis of the Pioneer batholith. One low of special interest is M30, an elongate feature associated with altered and mineralized hornblende-biotite granodiorite along the Comet fault zone (Berger and others, 1983).

About 40 km northwest of low M30, other parts of the Pioneer batholith are marked by highs. For example, M31 and M32 mark relatively magnetic components of younger and older intrusive rocks, respectively. Their subsurface sources extend northwestward beneath basin fill and surficial deposits. A cluster of highs labeled M33 and M34 demonstrate again the highly magnetic, though variable, character of older plutonic rocks. Highs M35 and M36 reflect older plutonic rocks that have intruded Belt Supergroup strata; M37 is a lower amplitude high associated with exposed younger plutonic rocks, mostly the Clifford Creek pluton (Snee, 1982). About 20 km northeast, the broad high-amplitude magnetic high M38 is associated with the Mount Fleecer stock, which is included by Snee (1982) as part of the Pioneer batholith but which has previously been considered a satellitic pluton of the Boulder batholith (Smedes and others, 1968; Tilling and others, 1968). About 15 km to the southeast, prominent magnetic high M39 is centered near Melrose, partly over mapped plutonic rocks of the Melrose stock. Because larger areas of mapped volcanic rocks short distances to the south and to the northwest have little or no magnetic expression, because a local gravity low noses across the magnetic high, and because the buried source lies beneath Paleozoic and Mesozoic sedimentary rocks, it is almost certain that the source is plutonic rocks, perhaps similar to those of the Mount Fleecer stock to the northwest or to those of the McCartney Mountain pluton (Chandler, 1973; Brumbaugh and Hendrix, 1981) 15 km southeast and associated with conspicuous magnetic high M40.

About 30 km southwest of the McCartney Mountain stock, four pronounced highs, M41 (a pair of highs) and M42–M44, are associated with various small exposures of plutonic rocks and larger tracts of volcanic rocks. Two knobs of M41 areally correspond, respectively, to the outcropping stock at Argenta and the cluster of small exposures of plutonic rock farther north. This anomaly outlines a single, largely buried pluton. High M42 presents an enigma. According to detailed mapping of R.C. Pearson, the center of M42 is on a thick sill that is a minimum of 130 m thick and 5 km wide at Grasshopper Creek and that is 15 km long. Although quantitative measurements of this rock's magnetization were not made, field checking using a hand magnet or compass needle indicates that it is moderately magnetic, typical of a plutonic rock of intermediate composition. However, because the mapped sill continues north from M42 across the magnetic depression between M41 and M42, several possibilities obtain: (1) The sill does not contribute significantly to M42 because it is too thin; (2) the northern part of the sill is thinner or more altered, or both, than the southern part; (3) the sill is really a laccolith that was fed by a stalk directly under M42. It is curious that the sill intrudes lavas of similar composition that cover a larger area than the sill and show no special magnetic response. Moderately mafic lavas, probably of anesitic to basaltic composition, overlie the sill locally and cover perhaps 20 percent of the area of M42 about the –100-nT contour, mainly on its east and northeast flank. However, these lavas probably average only 35 m thick in this area. High M43 is centered on the Blue Wing district, but the outcropping pluton is mainly north of the center of the anomaly and the stocks at Bannack are well down on the south flank of the anomaly. High M44 corresponds with basalt flows that may be very young, perhaps similar in age to Pliocene ones that overlie Archean rocks in the southern Ruby Range. The magnetic ridge that connects M43 and M44 remains enigmatic. Of great importance with regard to sources of highs M42, M43, and M44 is the fact that these anomalies are centered on flight lines 3 km apart. Thus, the actual centers of these anomalies could be a kilometer or more from those shown. This uncertainty of the location of anomaly crest may be especially significant with respect to high M43. The magnetic depression between highs M42 and M43 approximately coincides with a circular to elliptical arcuate feature shown on Landsat multispectral scanner imagery and possibly associated with a volcanic center, as noted by T.L. Purdy and L.C. Rowan. This anomalous circular pattern was evidently discovered first on aerial photography by an oil company geologist, who later noted the coincidence of the magnetic depression with the feature on multispectral imagery and who visited the area in 1976. According to the account of Meyer (1980), the discovery of the copper-molybdenum-silver porphyry deposit in the center of the circular feature is attributed to this oil company geologist.

It may be noted before leaving the Pioneer batholith area that magnetic "quiet zones" of low magnetic relief in regions of subsurface Phanerozoic sedimentary rocks may be significant terranes for hydrocarbon exploration. That is, if subsurface sedimentary rocks originally containing hydrocarbons have not been intruded by rocks hot enough to drive off these hydrocarbons, the rocks may still have economic potential. The strongest evidence for subsurface intrusive rocks consists primarily of magnetic highs and secondarily of gravity highs or lows, depending upon the density of the country rock. Magnetic quiet zones therefore imply the absence of intrusive rocks, unless gravity anomalies indicate otherwise, and of the absence of the adverse effects of excessive heat. A good example of a magnetic quiet zone is in a region of mapped Proterozoic sedimentary rocks contained in the Grasshopper thrust plate (Ruppel and others, 1981) within magnetic highs M17, M34, and M37, about 25 km east of Wisdom in the north-central Pioneer Mountains. Here, both magnetic and gravity anomaly data imply that the region is devoid of intrusive rocks. Thus, if Phanerozoic sedimentary rocks in the sole of the thrust plate originally contained hydrocarbons, it is possible that these fossil fuels have been retained and are thus targets for exploration. With regard to petroleum, there is no magnetic evidence here or elsewhere in the quadrangle of the occurrence of diagenetic magnetite or other magnetic minerals within basin fill that elsewhere (Donovan and others, 1979; Reynolds and others, 1990) has been identified in plumes overlying oil and gas deposits. However, any short-wavelength anomalies expected to be produced by such diagenetic magnetic minerals formed in a strong reducing environment are probably too small in amplitude to be detected in total-field surveys controlled by conventional techniques for eliminating diurnal variations of the Earth's field. Detection of anomalies caused by diagenetic magnetic minerals would probably require use of a magnetic gradiometer for acquiring data.

In the north-central part of the quadrangle other highs, such as M45 and M46, their sources extending beneath basin-fill and surficial deposits, are associated with plutonic rocks satellitic to either the Pioneer batholith or the Boulder Batholith, or both. Clearly associated with the Boulder batholith are high M47, associated with an exposed stock, and highs M48 and M49, which seem to be northward extensions of high M38, which is associated with the Mt. Fleecer stock. High M50, associated with the Burton Park pluton, and highs M51–M54, associated with the southern margin of the Boulder batholith, manifest the magnetic zonation of the batholith proper, which has long been known to be compositionally zoned (Knopf, 1957, 1964; Klepper, 1973; Tilling, 1973) and magnetically complex (Hanna, 1973; Geissman, Kelly, and others, 1980; Geissman, Van der Voo, and others, 1980). Even though many of the batholithic rocks in the quadrangle possess a stable reversed remanent magnetization, most of them also have sufficiently high magnetic susceptibilities to render total magnetizations normal (table 1), thereby causing highs to appear in spatial proximity to their sources. For example, the Hell Canyon pluton, extending northwest from M51, generates two magnetic highs and one low; the Rader Creek pluton, extending from M52 to M53, generates two magnetic highs. Both of these plutons possess reversed remanent magnetization. High M55, associated with younger plutonic rocks of the Moose Creek stock (Smedes and others, 1980), also known as the Humbug stock (Loen and Pearson, 1984), is low in amplitude. Magnetic low M56 at Butte and, perhaps, the low centered among highs M38, M48, and M55, mark the southern terminus of a belt of magnetic lows associated with mineralized ground throughout much of the interior northeast-southwest extent of the Boulder batholith (Hanna, 1969). East of the Jefferson River valley in the Tobacco Root Mountains, magnetic high M57 at the eastern edge of the quadrangle is associated with the main mass of the Tobacco Root batholith (Hess, 1967; Burger, 1969; Smith, 1970; Cordua, 1973; Hanely, 1975; Schmidt and Garihan, 1979; Vitaliano and others, 1979; Samuelson, 1981; Schmidt and Hendrix, 1981; Wilson, 1981; O'Neill, 1983). This magnetic high correlates with gravity low G43 (Burfeind, 1967), caused by the high density contrast between the Tobacco Root batholith and intruded metamorphic rocks.

Throughout the Archean metamorphic rock terrane in the eastern third of the quadrangle, sources of magnetic anomalies may take many forms, in particular, Cretaceous to Tertiary intrusive rocks or a variety of Precambrian metamorphic rocks. Precambrian rocks known to be magnetic include all bedded iron-formation and associated mafic to ultramafic rocks (DeMunck, 1956; James and Wier, 1960, 1972a; James, 1962; Wier, 1965; Burger, 1967; Bayley and James, 1973; Immega and Klein, 1975, 1976; Immega, 1976; James, 1981); some diabase and other mafic dikes (Wooden and others, 1978); and some amphibolites or amphibolite gneisses. In metamorphic rock terrane, plutonic rock sources of magnetic anomalies, if sufficiently voluminous in the subsurface, can be distinguished from metamorphic rock sources of magnetic anomalies by gravity lows associated with the plutonic rocks. However, if the magnetic intrusive rocks are quite limited in subsurface extent, the expected gravity low may be weak or have a short wavelength, thus making it difficult to distinguish from its metamorphic counterpart in a regional survey.

For example, magnetic highs M58 and M59, within 15 km north and northwest of M57, are in mining districts known to be partly intruded by plutonic rocks. However, because they correlate with projections of gravity highs and because they conform approximately with massive folded bodies of amphibolite (O'Neill, 1983), it is inferred that they are caused by the mafic metamorphic rocks. The same interpretation is given to sources of highs M60 and M61, about 15 km south of M57, based upon their correlation with broad gravity high G45. The amplitudes of these highs may be attributable to mapped iron-formation associated with mafic to ultramafic rocks (James, 1981).

Likewise, in the southeastern corner of the quadrangle, local high-amplitude magnetic highs correlate with gravity highs over a large tract of Archean metamorphic rocks in the Ruby range (Heinrich, 1960; Okuma, 1971; Tysdal, 1976; Dahl, 1977; Garihan, 1979; Karasevich, 1980, 1981). For example, M62 is associated with iron-formation (James and Weir, 1972b) and a body of pyroxene-rich hornblendite. Similarly, highs M63–M68 represent metamorphic rock sources, either subsurface iron-formation associated with mafic to ultramafic rocks or subsurface amphibolite-rich rocks.

Northwest of the Ruby Range, within less than 10 km of the mountain front, a series of magnetic highs, M69–M73, are in an extensive area of basin-fill and surficial deposits. Here there are no surficial clues about the sources of these anomalies. Gravity data for this region are greatly influenced by occurrences of basin-fill deposits in the deepest parts of the valleys; therefore, the use of gravity data to identify the types of magnetic-anomaly source is not straightforward. Even though high M69 coincides with gravity low G13 and suggests the presence of a pluton beneath the thickened basin fill here, highs M70 and M71 (see Lankston and Lankston, 1986), and also M72 and M73, are associated with flanks of gravity highs or with slight increases of the gravity field where the field is regionally depressed. Thus, if the sources of all of the highs, including M69, are similar, the gravity data suggest that they are metamorphic, perhaps iron-formation, mafic to ultramafic rocks (including diabase or lamprophyre dikes), or amphibolite-rich rocks. The apparent continuity of highs M69 and M70 suggests, but does not prove, the presence of metamorphic rock sources, rather than plutons. The resolution of the ambiguity of the nature of these anomaly sources awaits more detailed and more diverse geophysical work, given the absence of drilling.

LOCATIONS OF SUBSURFACE MAGNETIC ROCKS

Because the great majority of mineral occurrences in the Dillon quadrangle show critical spatial relationships to plutonic rocks, and because most plutonic rocks in the quadrangle can be expected to be magnetic, it is useful to produce a map showing locations of significant amounts of subsurface magnetic rocks, while discriminating plutonic from metamorphic rock sources; gravity data tend to distinguish plutonic from dense metamorphic rock sources. Such a map of subsurface magnetic rocks (fig. 6) has been produced on the assumption that anomaly sources are bounded by steep sides. It is further assumed that the sources are sufficiently thick and steep-sided to generate anomalies that, when transformed to pseudogravity anomalies and second-vertical-derivative anomalies, approximately delineate their boundaries in plan view.

Three such maps have been derived while data processing techniques have improved or while new data have become available, the two preliminary ones having been used in early stages of mineral resource assessment using ore occurrence models. The third (fig. 6), shown at small scale, was derived according to the following sequence of steps: (1) data from the six diverse local surveys and one regional survey were merged by analytical continuation and smoothing techniques into a single gridded data set; (2) the level of this merged data set was adjusted to match data from a recently flown survey of the Butte quadrangle to the north; (3) the adjusted data grid was extended by regional data 15 minutes of latitude and longitude beyond the quadrangle boundaries to reduce unwanted edge effects associated with subsequent filtering; (4) the pseudogravity gradient map (fig. 5) was computed and contoured; (5) elongate crests of gradient maxima were plotted and axial traces along these crests were drawn by hand; (6) the reduced-to-pole map was computed from the original merged data set and was contoured (fig. 3); (7) the reduced-to-pole map was compared with the generalized geologic map, from which it was noted that the zero-contour lines approximately outline a number of mapped occurrences of magnetic igneous rocks (properties known from rock magnetic measurements); (8) a second-vertical-derivative map of reduced-to-pole anomalies was computed, bandpass filtered, and contoured, to note the zero level; (9) heavy solid lines of crest traces from step 5 were drawn only where they approximately coincided with zero contours of the reduced-to-pole map from step 6; and (10) at solid line discontinuities, a combination of zero contour lines of both the reduced-to-pole map from step 6 and the filtered second-vertical-derivative map from step 8 were used to guide the connecting of solid lines. The resulting solid lines bound with a high degree of certainty regions of significant amounts of subsurface magnetic rocks, assumed at shallow depth to have steep sides.

In addition to these lines or segments of lines (which bound regions shown on fig. 6), figure 6 shows a series of spot locations that correspond to maximum values of the magnitude of pseudogravity horizontal gradient (Blakely and Simpson, 1986). These spot locations mark other edges of magnetic-anomaly sources, assuming that these sources have steep boundaries in the shallow subsurface. A special significance of the boundary lines and spot locations is that where mapped rocks that are characteristically magnetic occur **outside** the boundary lines or spot locations, the mapped rocks at these locations either are very thin, uncharacteristically nonmagnetic (perhaps because of pervasive alteration), or contained by boundaries that are not steep.

SUMMARY AND CONCLUSIONS

ANOMALIES AND LITHOLOGY

On a regional scale, most gravity lows are associated with basin-fill deposits and plutonic rock bodies, whereas most gravity highs are associated with high-grade metamorphic rocks or with moderately dense Paleozoic and Mesozoic sedimentary rocks. In contrast, most magnetic highs are associated with either plutonic or mafic metamorphic rock bodies having total magnetizations that are normal in polarity. Some magnetic lows over mapped intrusive rocks may manifest regions that have been hydrothermally or deuterically altered and consequently enriched in metallic minerals. On the basis of thermomagnetic work and inspection of polished rock sections, the anomaly-causing mineral in plutonic rocks is inferred to be magnetite; in volcanic rocks, titanomagnetite; and in mafic metamorphic rocks, either magnetite or titanomagnetite, depending upon composition. Iron-formation is the most strongly magnetic rock type in the quadrangle. In general, both induced and remanent magnetization are important contributors to magnetic anomalies. Much of the magnetic remanence is inferred to be isothermal and of the viscous type, a conclusion based on partial demagnetization of rock samples in alternating magnetic fields. Some topographically elevated igneous and metamorphic rocks may generate short-wavelength, large-amplitude magnetic highs as a result of acquiring strong isothermal remanent magnetization caused by lightning discharges. In some cases, these short-wavelength features can be detected only in magnetic anomaly data sets derived from airborne traverses spaced 0.8 km or closer. Magnetic zonation associated with plutonic rock bodies, such as the Pioneer batholith, appears to correlate with rock compositions that are increasingly mafic outwards. The large amplitudes of highs at the periphery of such bodies sometimes may be augmented by additive signatures associated with magnetic skarn.

There are two important sets of relationships for interpreting regional subsurface geology in the quadrangle: (1) In regions of basin-fill deposits, the relative amplitudes of gravity lows indicate the relative depths of fill, within the uncertainty constraints of lateral density contrasts; and (2) in terranes of high-grade metamorphic rocks, magnetic plutonic bodies can be differentiated from magnetic metamorphic bodies, such as amphibolite, on the basis of gravity lows associated with the lower density plutonic rocks. Where plutonic rocks intrude Proterozoic sedimentary rocks having a similar density, little, if any, significant anomaly is produced; where plutonic rocks, such as the Tobacco Root batholith, intrude Archean metamorphic rocks, a conspicuous high-gradient gravity low is produced.[1]

ANOMALIES AND STRUCTURE

Several major fault systems mapped within the quadrangle (Ruppel and others, 1981, 1983) have anomaly signatures. For example, the Beaverhead Divide fault zone containing numerous reverse faults of mid-Proterozoic ancestry in the southwestern part of the quadrangle coincides in large part with a belt of magnetic highs (M7–M9); these highs are inferred to result from Cretaceous or Tertiary plutons intruded into this ancient zone of crustal weakness. On the basis of magnetic and gravity data, it may be postulated that the east-trending Badger Pass fault zone, in the south-central part of the quadrangle, may extend as far west as the Beaverhead Divide fault zone and as far northeast as a belt of magnetic highs (M69–M73) about 10 km northwest of the front of the Ruby Range. The northwest-trending Blacktail fault and the northeast-trending fault fronting the Ruby Range, both in the southeastern part of the quadrangle, coincide with steep gravity and magnetic gradients. The subsurface connection of the Camp Creek fault and the Willow Creek fault, a structure marking the edge of the inferred Belt basin (not shown) in the northeastern part of the quadrangle, is obscured by intrusive rocks clearly shown on the magnetic anomaly map. Inferred faults bounding the major basins, such as the Big Hole basin and the inferred basin of the Jefferson River valley are steep—within less than 20° of vertical—at least for vertical distances of 1–2 km or more. On a subcontinental scale, O'Neill and Lopez (1985) used linear gravity and magnetic anomalies to help define the northeast-trending Great Falls tectonic zone that transects the Dillon quadrangle.

Some local anomalous features delineate local faults. For example, a magnetic low is associated with altered and mineralized plutonic rock along the Comet zone, and a magnetic lineament was detected by Gay (1972, p. 14) along the Continental fault near the northeastern margin of the quadrangle.

ANOMALIES AND FLOORS OF BASINS

The map showing regions underlain by magnetic rocks (fig. 6), when compared with maps of generalized geology and Bouguer gravity anomalies (map B), can be used to infer the nature of bedrock underlying basin fill of Tertiary and Quaternary age. For example, these maps suggest that all of the width of the Big Hole basin north of about lat 45°41.5′ N. and the eastern two-thirds of the width of this basin between lat 45°25′ N. and lat 45° 37.5′ N. are floored largely by nonmagnetic Proterozoic rocks. Other parts of the basin are underlain largely by magnetic rocks, presumably plutons that intrude thrust sheets at depth. Similarly, these maps show that basin fill of upper Grasshopper Creek and of Horse Prairie valley are floored largely by nonmagnetic Proterozoic and Paleozoic rocks. Basin fill of the Jefferson River valley is inferred to be floored by relatively nonmagnetic Archean and Paleozoic rocks, as is much of the fill of the Beaverhead River valley. About a quarter of the areally mapped basin fill of the Beaverhead River valley is inferred to be underlain by magnetic Archean rocks.

ANOMALIES AND MINERAL OCCURRENCES

The single most important relationship between anomalies and mineral occurrences is the correlation of magnetic highs with subsurface plutonic rocks, which in turn are spatially related to such occurrences as hydrothermal vein and replacement deposits, porphyry and stockwork deposits, and skarns. The magnetic data are particularly useful for delineating hidden subsurface lateral extensions of plutons, such as the Bloody Dick stock, which the data now indicate is batholithic in size. Completely buried plutons, such as those paralleling the Beaverhead Divide fault zone in the Pratt Creek, Eldorado, Kirtley Creek, and Carmen Creek mining districts, can generally be distinguished from buried magnetic metamorphic rocks by means of gravity data because of the higher densities of metamorphic rocks. In places, the magnetic data show that plutonic rocks have intruded favorable hosts for mineralization, such as carbonates, as expressed by the northwest-trending nose of magnetic high M20, which marks a hidden apophysis of a pluton extending beneath the Hecla mining district. At still other places, mineral occurrences

[1]Information from a mineral-exploration bore hole located in the northern part of the Argenta mining district, about 3.2 km north-northwest of the village of Argenta, was made available to the authors after completion of the study. Our geophysical studies suggested that this region is underlain by plutonic rocks (fig. 6); the new information indicates that it is underlain by metamorphic rocks. Strata in the bore hole, which was drilled to a depth of 336 m, are divisible into three parts: an upper unit, 80 m thick, consisting of quartzarenite of probable Cambrian age; a middle unit, 220 m thick, consisting of sandstone and argillite belonging to the Belt Supergroup; and a lower unit, consisting of Archean biotite-quartz schist that is in depositional contact with the overlying Proterozoic rocks. Both sedimentary rock units are intruded by sills that probably are apophyses of the Argenta granodiorite stock, centered on the village of Argenta. The bore hole information serves as an excellent illustration of the difficulty of distinguishing subsurface plutonic rocks from subsurface metamorphic rocks if the plutonic rocks are intermediate in composition and the metamorphic rocks are very quartz-rich.

correlate spatially with the middle-to-upper flanks of magnetic highs, not associated with topography, such as the gradient of high M22 over a region containing magnetite-rich skarn in Paleozoic rocks.

The magnetic data also may have significance for hydrocarbon exploration in an indirect way. Magnetic "quiet zones" (regions of low magnetic relief) may mark areas that are devoid of plutonic rock in the subsurface and, thus, areas that have not been subjected to much magmatic heat. Where potentially petroliferous rocks occur in the subsurface in such a magnetic quiet zone, chances are improved for retention of hydrocarbons constituting a fossil fuels resource. Such a magnetic quiet zone is present in the north-central Pioneer Mountains where Proterozoic rocks have been thrust over younger sedimentary rocks fringed by magnetic highs M17, M34, and M37.

Of peripheral interest to resource assessment, the thicknesses of basin fill estimated from gravity anomaly data may have significance in two ways: (1) bracketing estimated volumes of placer deposits, sedimentary deposits of secondary uranium minerals, or fossil fuels that may be contained **within** the basin fill; and (2) determining minimum depths to exploitation of mineral deposits that may occur **beneath** the basin fill.

Of unknown significance, magnetic highs also spatially correlate with magnetic units of Archean metamorphic rocks in the southeastern part of the quadrangle. For example, high M62 in the Ruby Range is caused principally by a thick mapped iron-formation. Although most other highs over the Archean metamorphic terrane may be associated with amphibolite, a number of them could be associated with iron-formation or ultramafic rocks having potential for heavy metals.

Table 1. *Physical properties of selected rock units, Dillon $1^{o} \times 2^{o}$ quadrangle, Idaho and Montana*

[No. on map A, sample locality; n, number of samples; Rem J, magnitude of remanent magnetization[1], exclusive of demagnetization effects, in SI units of A/m; k, apparent magnetic susceptibility, in dimensionless SI units of 10^{-2}; Q, Koenigsberger ratio of remanent to induced magnetization, assuming an ambient magnetic-flux density of 0.575 gauss; total J, magnitude of total magnetization, in SI units of A/m (values enclosed by brackets represent maxima on the assumption that the remanent and induced magnetization have the same direction and polarity; values enclosed by braces, such as {1.79}, represent the only magnetization measurement available); polarity total J, polarity of the total magnetization vector; bracketed polarities, such as [19.2], are inferred on the basis of Q values rather than direct measurements (N = normal; R = reversed; I = intermediate); ρ, dry bulk density (g/cm^3); —, data not available]

No. on map A	Rock Unit	n	Rem J	k	Q	Total J	Polarity total J	ρ	References[2]
1	Early mafic pluton	8	1.12	2.73	0.90	2.24	N	2.68	1
2	Rader Creek pluton	13	0.355	5.64	.14	2.24	N	2.74	1
3	Rader Creek pluton	6	1.24	4.41	.61	1.36	I	2.71	1
4	Rader Creek pluton	8	.362	5.68	.14	2.25	N	2.74	1
5	Rader Creek pluton	10	2.97	4.54	1.4	1.13	R	2.74	1
6	Butte Quartz Monzonite	12	.205	3.97	.11	2.02	N	2.71	1
7	Butte Quartz Monzonite	14	.229	3.67	.14	1.88	N	2.71	1
8	Butte Quartz Monzonite	14	.161	3.63	.097	1.80	N	2.70	1
9	Butte Quartz Monzonite	7	.262	0.692	.83	0.564	N	2.61	1
10	Homestake pluton	13	.137	1.70	.18	.900	N	2.64	1
11	Donald pluton	15	.338	2.96	.25	1.70	N	2.68	1
12	Hell Canyon pluton	8	.495	3.73	.29	1.25	N	2.66	1
13	Climax Gulch pluton	10	15.1	2.80	12	14.8	I	2.68	1
14	Climax Gulch pluton	22	.417	3.78	.24	2.10	N	2.69	1
15	Satellite pluton	13	.264	3.76	.15	1.74	N	2.81	1
16	Lowland Creek Volcanics	13	.391	7.95	11	.369	R	2.46	8
17	Lowland Creek Volcanics	16	1.01	8.39	26	.981	R	2.45	8
18	Tertiary volcanics, Beaverhead River valley.	21	4.31	.249	38	4.42	N	2.60	8
18	Scoria, Beaverhead River valley.	5	15.0	.289	113	[15.1]	N	1.88	2, 3
18	Basalt, Beaverhead River valley.	9	.80	.226	7.7	[0.904]	N	2.60	2, 3
19	Volcanics, Bone Basin	9	.84	1.63	1.1	.30	I	2.63	2, 3
19	Volcanics, Bone Basin	10	8.6	4.40	4.3	6.8	R	2.60	2, 3
19	Volcanics, Bone Basin	9	1.2	2.89	.91	.46	I	2.57	2, 3
19	Volcanics, Bone Basin	9	.16	.603	.58	.14	I	2.49	2, 3
20	Vesicular andesite, Divide.	5	19.0	.402	103	[19.2]	N	2.33	2, 3

Table 1. *Physical properties of selected rock units, Dillon 1°×2° quadrangle, Idaho and Montana*—**Continued**

No. on map A	Rock Unit	n	Rem J	k	Q	Total J	Polarity total J	ρ	References[2]
21	Basalt, Beaverhead River valley.	5	3.80	.615	13	[4.80]	N	2.62	2, 3
22	Vesicular latite, Beaverhead River valley.	5	15.0	.137	137	[15.1]	N	2.39	2, 3
23	Vesicular latite, Beaverhead River valley.	4	1.10	.201	12	[1.19]	—	2.30	2, 3
24	Latite, Beaverhead River valley.	5	12.0	.176	149	[12.1]	N	2.46	2, 3
25	Basalt, Beaverhead River valley.	4	.29	.929	.68	[0.716]	—	2.73	2, 3
26	Amphibolite, Pony Group.	12	1.23	.180	15	1.31	N	—	4
27	Archean marble	1	0	.0126	0	—	[N]	2.84	5
28	Archean iron-formation	1	100	251	.869	215	—	2.98	5
29	Archean biotite schist	1	.001	.235	.009	.108	[N]	3.65	5
30	Archean talc schist	1	0	.0754	0	.060	[N]	2.75	5
31	Proterozoic siltstone	1	.526	.0364	31	.526	—	2.64	6
32	Proterozoic siltstone	1	.505	.0440	25	.503	—	2.64	6
33	Cretaceous granodiorite.	1	.728	4.38	.36	1.69	[N]	2.66	6
33	Cretaceous granodiorite.	1	2.17	3.24	1.5	3.10	—	2.65	6
34	Proterozoic siltstone	1	1.18	.0239	108	1.17	—	2.67	6
35	Proterozoic dolomite	1	0	.0025	0	.001	[N]	2.58	6
36	Mississippian carbonate.	1	.002	.0088	.50	.005	—	2.58	6
37	Quartz monzonite, Moose Creek stock.	1	.046	5.03	.02	[2.35]	N	—	7
38	Granodiorite, Moose Creek stock.	1	1.50	1.26	2.6	[2.08]	—	—	7
39	Monzogranite	1	.0024	.187	.028	[0.088]	[N]	2.62	9
40	Granodiorite	1	.786	6.27	.27	[3.65]	[N]	2.55	9
41	Proterozoic foliated rock	1	.040	.0691	1.3	[0.072]	—	2.60	9
42	Granodiorite	1	.010	.251	.087	[0.125]	[N]	2.62	9
43	Tuffaceous siltstone	1	.002	.0503	.087	[0.025]	[N]	2.20	9
44	Quartzite	1	.003	.0100	.6	[0.0076]	—	2.60	10
45	Diorite(?).	1	.002	.0226	1.19	[0.012]	—	2.67	10
46	Granite	1	.593	2.24	.58	[1.62]	—	2.65	10
47	Granite	1	1.44	4.15	.76	[3.34]	—	2.76	10
48	Quartzite	1	.001	.0025	.80	[0.002]	—	2.61	10
49	Quartz diorite	1	.212	3.46	.13	[1.79]	[N]	2.62	10

Table 1. *Physical properties of selected rock units, Dillon 1°×2° quadrangle, Idaho and Montana*—Continued

No. on map A	Rock Unit	n	Rem J	k	Q	Total J	Polarity total J	ρ	References[2]
50	Quartz diorite	1	.016	3.07	.011	[1.42]	[N]	2.62	10
51	Granodiorite	1	.030	2.60	.025	[1.22]	[N]	2.59	10
52	Granodiorite	1	.585	.816	1.6	[0.958]	—	2.58	10
53	Quartzose sandstone	1	.006	.0113	1.2	[0.011]	—	2.64	10
54	Quartzite	1	.003	.00251	2.6	[0.004]	—	2.59	10
55	Quartzite	1	.002	.00754	.6	[0.005]	—	2.61	10
56	Quartzite	1	.002	.0126	.3	[0.008]	—	2.57	10
57	Granodiorite	1	.060	3.09	.042	[1.47]	—	2.60	10
58	Quartzite	1	.004	.0339	.24	[0.020]	—	2.70	10
59	Mafic plutonic rock	1	.282	6.31	.098	[3.17]	[N]	3.24	10
60	Siliceous soil	1	.002	1.31	.003	[0.600]	[N]	2.62	10
61	Granite	1	.003	.0188	.38	[0.012]	—	2.58	10
61	Granite	1	.007	1.04	.015	[0.485]	[N]	2.63	10
62	Dolomite	1	.004	.0503	.15	[0.027]	[N]	2.59	10
63	Granite	1	.010	4.08	.006	[1.88]	[N]	2.69	10
64	Mafic dike	1	.046	3.39	.030	[1.60]	[N]	2.80	10
65	Mafic dike	1	.026	2.74	.021	[1.28]	[N]	2.84	10
66	Granite	1	.002	1.01	.28	[0.009]	—	2.62	10
67	Volcanic rock	1	.071	.252	.62	[0.186]	—	2.59	10
68	Porphyritic granite	1	.270	1.04	.57	[0.745]	—	2.62	10
69	Granite	1	.060	2.02	.065	[0.986]	[N]	2.65	10
70	Granodiorite	1	.005	3.68	.003	[1.69]	[N]	2.69	10
71	Granodiorite	1	.007	3.96	.004	[1.82]	[N]	2.67	10
72	Quartz diorite	1	.454	12.3	.081	[6.08]	—	2.87	10
73	Quartz monzonite	1	.801	3.99	.44	2.61	N	2.68	11
74	Mesozoic clastic rock	1	—	—	—	—	—	2.61	11
75	Mesozoic clastic rock	1	.00205	.0425	.10	[0.0185]	—	2.71	11
76	Vesicular basalt	1	2.24	.342	14	2.12	I	2.42	11
77	Granodiorite	1	.0916	.641	.31	.351	N	2.71	11
78	Granodiorite (weathered)	1	2.59	2.56	2.2	2.04	N	2.60	11
79	Granodiorite (weathered)	1	2.05	.0474	95	2.05	I	2.49	11
80	Granodiorite	1	3.69	2.75	2.9	4.82	N	2.75	11
81	Granodiorite	1	7.61	2.76	6.0	7.47	I	2.69	11
82	Granodiorite	1	14.8	3.19	10	16.0	N	2.78	11
83	Granite (weathered)	1	—	—	—	—	—	2.55	11

Table 1. *Physical properties of selected rock units, Dillon 1°×2° quadrangle, Idaho and Montana*—Continued

No. on map A	Rock Unit	n	Rem J	k	Q	Total J	Polarity total J	ρ	References[2]
84	Granodiorite	1	1.54	2.22	1.5	2.55	N	2.72	11
85	Granite (weathered)	1	.00270	—	—	{0.00270}	N	2.53	11
86	Quartz monzonite (weathered)	1	—	—	—	—	—	2.56	11
87	Quartz monzonite	1	—	—	—	—	—	2.62	11
88	Quartz monzonite	1	—	—	—	—	—	2.68	11
89	Granodiorite	1	.728	3.64	.44	2.21	N	2.67	11
90	Quartz monzonite	1	—	—	—	—	—	2.67	11
91	Quartz monzonite	1	—	—	—	—	—	2.70	11
92	Quartz monzonite	1	—	—	—	—	—	2.71	11
93	Granodiorite	1	.675	2.19	.67	1.40	N	2.68	11
94	Archean carbonate	1	—	—	—	—	—	2.65	11
95	Granodiorite (weathered)	1	7.30	3.39	4.7	8.72	N	2.54	11
96	Quartz monzonite (weathered)	1	.445	3.43	.28	1.98	N	2.59	11
97	Archean amphibolite	1	.692	1.71	1.89	[1.47]	—	3.02	11
98	Archean gneiss	1	—	—	—	—	—	2.69	11
99	Archean amphibolite	1	.0282	.0557	1.1	[0.137]	—	2.95	11
100	Archean gneiss	1	—	—	—	—	—	2.70	11
101	Archean gneiss	1	—	—	—	—	—	2.74	11
102	Archean gneiss	1	—	—	—	—	—	2.59	11
103	Archean gneiss	1	.00410	.0127	.71	[0.00991]	—	2.66	11
104	Archean gneiss	1	—	—	—	—	—	2.63	11
105	Archean amphibolite	1	—	—	—	—	—	3.02	11
106	Archean gneiss	1	—	—	—	—	—	2.61	11
107	Granodiorite	1	—	—	—	—	—	2.65	11
108	Quartz monzonite	1	—	—	—	—	—	2.64	11
109	Quartz monzonite	1	—	—	—	—	—	2.67	11
110	Quartz monzonite	1	—	—	—	—	—	2.69	11
111	Quartz monzonite	1	—	—	—	—	—	2.70	11
112	Quartz monzonite	1	—	—	—	—	—	2.72	11
113	Quartz monzonite	1	—	—	—	—	—	2.73	11
114	Gabbro, Ringing Rocks pluton	1	6.56	2.56	5.6	7.70	N	2.87	11
115	Cretaceous granodiorite.	1	—	3.92	—	{1.79}	—	2.60	12
116	Cretaceous granite	1	—	.669	—	{0.0306}	—	2.57	12
117	Cretaceous granite	1	—	2.80	—	{1.28}	—	2.64	12
118	Cretaceous granite	1	—	1.17	—	{0.536}	—	2.54	12

Table 1. *Physical properties of selected rock units, Dillon $1^o \times 2^o$ quadrangle, Idaho and Montana*—Continued

No. on map A	Rock Unit	n	Rem J	k	Q	Total J	Polarity total J	ρ	References[2]
119	Cretaceous granodiorite	1	—	4.27	—	{1.95}	—	2.68	12
120	Cretaceous granodiorite	1	—	4.68	—	{2.14}	—	2.72	12
121	Cretaceous granite	1	—	1.58	—	{0.723}	—	2.62	12
122	Cretaceous granodiorite	1	—	1.49	—	{0.682}	—	2.74	12
123	Proterozoic clastic rock	1	—	.0343	—	{0.0157}	—	2.66	12
124	Proterozoic clastic rock	1	—	.0415	—	{0.0190}	—	2.65	12
125	Cretaceous volcanic rock	1	—	1.30	—	{0.595}	—	2.54	12
126	Proterozoic clastic rock	1	—	.0266	—	{0.0122}	—	2.00	12
127	Tertiary tuff	1	—	.00720	—	{0.00330}	—	2.45	12
128	Paleozoic sedimentary rock	1	—	.0147	—	{0.00673}	—	2.68	12
129	Cretaceous volcanic rock	1	—	.148	—	{0.0678}	—	2.75	12
130	Archean gneiss (weathered)	1	—	—	—	—	—	2.60	12
131	Cretaceous granodiorite	1	—	—	—	—	—	2.64	12
132	Cretaceous granodiorite	1	—	—	—	—	—	2.61	12
133	Cretaceous granodiorite	1	—	—	—	—	—	2.62	12
134	Cretaceous granodiorite	1	—	—	—	—	—	2.66	12
135	Cretaceous granodiorite	1	—	—	—	—	—	2.62	12
136	Archean gneiss	1	—	—	—	—	—	2.85	12
137	Archean gneiss	1	—	—	—	—	—	2.81	12
138	Tertiary tuff	1	—	—	—	—	—	2.16	12
139	Archean carbonate rock	1	—	—	—	—	—	2.63	12
140	Archean gneiss	1	—	—	—	—	—	2.99	12
141	Tertiary tuff	1	—	—	—	—	—	2.54	12
142	Archean carbonate rock	1	—	—	—	—	—	2.62	12
143	Archean carbonate rock	1	—	—	—	—	—	2.65	12
144	Archean gneiss	1	—	—	—	—	—	2.70	12
145	Archean gneiss	1	—	—	—	—	—	2.86	12
146	Tertiary basalt	1	—	—	—	—	—	2.74	12
147	Tertiary basalt	1	—	—	—	—	—	2.52	12
148	Tertiary vesicular basalt	1	—	—	—	—	—	1.72	12
149	Paleozoic sedimentary rock	1	—	—	—	—	—	2.69	12
150	Tertiary basalt	1	—	—	—	—	—	2.63	12
151	Paleozoic sedimentary rock	1	—	—	—	—	—	2.64	12
152	Tertiary rhyolitic tuff	1	—	—	—	—	—	2.12	12
153	Tertiary rhyodacite	1	—	—	—	—	—	2.59	12

Table 1. *Physical properties of selected rock units, Dillon 1°×2° quadrangle, Idaho and Montana*—Continued

No. on map A	Rock Unit	n	Rem J	k	Q	Total J	Polarity total J	ρ	References[2]
154	Mesozoic sedimentary rock	1	—	—	—	—	—	2.30	12
155	Mesozoic sedimentary rock	1	—	—	—	—	—	2.33	12
156	Mesozoic sedimentary rock	1	—	—	—	—	—	2.63	12
157	Tertiary tuff	1	—	—	—	—	—	2.48	12
158	Tertiary tuff	1	—	—	—	—	—	2.13	12
159	Mesozoic sedimentary rock	1	—	—	—	—	—	2.66	12
160	Paleozoic sedimentary rock	1	—	—	—	—	—	2.58	12
161	Paleozoic sedimentary rock	1	—	—	—	—	—	2.59	12
162	Cretaceous granodiorite	1	—	—	—	—	—	2.69	12
163	Cretaceous granodiorite	1	—	—	—	—	—	2.65	12
164	Mesozoic sedimentary rock	1	—	—	—	—	—	2.64	12
165	Cretaceous granodiorite	1	—	—	—	—	—	2.70	12
166	Mesozoic sedimentary rock	1	—	—	—	—	—	2.68	12
167	Mesozoic sedimentary rock	1	—	—	—	—	—	2.68	12
168	Archean gneiss	1	—	—	—	—	—	2.70	12
169	Paleozoic sedimentary rock	1	—	—	—	—	—	2.77	12
170	Cretaceous granodiorite (mafic)	1	—	—	—	—	—	2.82	12
171	Cretaceous granite	1	—	—	—		—	2.63	12
172	Tertiary tuff	1	—	—	—	—	—	2.58	12
173	Tertiary tuff	1	—	—	—	—	—	2.39	12
174	Tertiary tuff	1	—	—	—	—	—	2.46	12
175	Cretaceous granodiorite	1	—	—	—	—	—	2.72	12
176	Mesozoic sedimentary rock	1	—	—	—	—	—	2.81	12
177	Cretaceous granodiorite (mafic)	1	—	—	—	—	—	2.84	12
178	Paleozoic sedimentary rock	1	—	—	—	—	—	2.57	12
179	Proterozoic clastic rock	1	—	—	—	—	—	2.62	12
180	Cretaceous granodiorite	1	—	—	—	—	—	2.61	12
181	Proterozoic clastic rock (float?).	1	—	—	—	—	—	2.63	12
182	Cretaceous granodiorite	1	—	—	—	—	—	2.68	12
183	Cretaceous granodiorite (mafic float).	1	—	—	—	—	—	2.81	12
184	Cretaceous granite	1	—	—	—	—	—	2.65	12
185	Cretaceous granite (weathered)	1	—	—	—	—	—	2.57	12
186	Cretaceous granite	1	—	—	—	—	—	2.63	12

Table 1. *Physical properties of selected rock units, Dillon $1^{o}\times2^{o}$ quadrangle, Idaho and Montana*—Continued

No. on map A	Rock Unit	n	Rem J	k	Q	Total J	Polarity total J	ρ	References[2]
187	Tertiary granite	1	—	—	—	—	—	2.60	12
188	Cretaceous granodiorite	1	—	—	—	—	—	2.65	12
189	Tertiary granodiorite	1	—	—	—	—	—	2.63	12
190	Tertiary granite (weathered)	1	—	—	—	—	—	2.39	12
191	Cretaceous granodiorite	1	—	—	—	—	—	2.64	12
192	Proterozoic clastic rock	1	—	—	—	—	—	2.70	12
193	Tertiary granodiorite	1	—	—	—	—	—	2.68	12
194	Proterozoic clastic rock	1	—	—	—	—	—	2.70	12
195	Proterozoic clastic rock	1	—	—	—	—	—	2.84	12
196	Proterozoic clastic rock	1	—	—	—	—	—	2.63	12
197	Proterozoic clastic rock	1	—	—	—	—	—	2.64	12
198	Proterozoic clastic rock	1	—	—	—	—	—	2.67	12
199	Tertiary granodiorite (weathered).	1	—	—	—	—	—	2.58	12
200	Proterozoic clastic rock	1	—	—	—	—	—	2.70	12
201	Proterozoic quartz monzonite	1	—	—	—	—	—	2.63	12
202	Tertiary volcanic rock	1	—	—	—	—	—	2.56	12
203	Tertiary volcanic rock	1	—	—	—	—	—	2.48	12
204	Cretaceous granodiorite (weathered).	1	—	—	—	—	—	2.59	12
205	Proterozoic clastic rock	1	—	—	—	—	—	2.66	12
206	Elkhorn Mountains Volcanics, hypabyssal intrusive.	10	.068	.778	.19	.421	N	2.73	2, 3
207	Boulder batholith, Pipestone	5	.021	.352	.13	.181	N	2.70	2, 3
207	Elkhorn Mountains Volcanics, thermally metamorphosed, Pipestone.	4	.420	6.41	.14	3.33	N	2.94	2, 3
208	Tertiary basalt (vesicular)	10	12.0	.678	39	[12.3]	N	2.43	2, 3
209	Tertiary basalt (altered)	9	.720	.804	2	[1.09]	N	2.78	2, 3

[1]Magnetization in SI units of A/m may be converted to electromagnetic units of emu/cm^3 by dividing by 10^3; volume susceptibility in dimensionless SI units may be converted to electromagnetic units by dividing by 4π; density in g/cm^3 may be converted to SI units of kg/m^3 by multiplying by 10^3.

[2]References: (1) Hanna (1973); (2) Hanna (1967); (3) Hanna (1965); (4) Colville (1961); (5) J.H. Hassemer and W.F. Hanna, unpub. data for the Ruby Mountains Wilderness Study Area, 1983 (compare with data of Pinckney and others (1980) for an area 20 mi east of the Dillon quadrangle); (6) J.H. Hassemer and W.F. Hanna, unpub. data for the Farlin Creek Wilderness Study Area, 1983 (see also Pearson and others, 1987); (7) Hanna (1980); (8) Hanna (1977a); (9) H.E. Kaufmann, J.H. Hassemer, and W.F. Hanna, unpub. data for the Anaconda-Pintlar Wilderness Study area, 1988 (see also Elliott and others, 1983); (10) H.E. Kaufmann and W.F. Hanna, unpub. data for the Pioneer Mountains, 1981 (see also Pearson and others, 1983, and Berger and others, 1983); (11) W.F. Hanna and Arthur Conradi, Jr., unpub. data, 1971; (12) H.E. Kaufman, unpub. data, 1983.

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