

Geophysical Interpretations of the Libby Thrust Belt, Northwestern Montana

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By M. Dean Kleinkopf

With a section on
Deep Folds and Faults Interpreted from Seismic Data
By Jack E. Harrison

And a section on Interpretation of Magnetotelluric Soundings
By W.D. Stanley

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GEOPHYSICAL INTERPRETATIONS OF THE LIBBY THRUST BELT, NORTHWESTERN MONTANA

By M. Dean Kleinkopf

ABSTRACT

Interpretations of gravity and aeromagnetic anomaly data, as well as results from two seismic reflection profiles and five magnetotelluric soundings, were used to study buried structure and lithology of the Libby thrust belt of northwestern Montana. Gravity modeling, supplemented by structural data from the seismic reflection profiles and geologic constraints derived from projection of surface geology, measured sections, and lateral consistency of sills, leads to the interpretation that thrust slices of folded crystalline basement form the core of the Purcell anticlinorium and Sylvanite anticline, which consist mainly of rocks of the Middle Proterozoic Belt Supergroup.

Gravity anomaly data show marked correlation with major structure of the area. The Purcell anticlinorium exhibits positive anomalies in excess of 20 mGal and the Sylvanite anticline anomalies in excess of 10 mGal. In the northern part of the study area, a distinct northwest-trending high-gradient zone suggests that a buried crustal shear zone may be present just north of Libby. The Rainy Creek and Bobtail Creek stocks, which show distinct positive magnetic anomalies, lie along this trend, and their emplacement may have been influenced by the postulated zone of deformation.

The most distinct magnetic anomalies in the principal study area are five positive anomalies associated with Cretaceous or younger cupolas and stocks that either are exposed or are known from drillholes to be present in the near-surface. Amplitudes range from 100 to more than 3,000 nT. Short-wavelength anomalies are associated with outcrops of magnetite-bearing sedimentary rocks of the Ravalli Group of the Belt Supergroup. A strip of high magnetic gradient correlates with the Hope fault zone. Modeling of the magnetic anomaly data was not done because of the absence of long-wavelength magnetic anomalies having likely sources in deeply buried Proterozoic crystalline basement. The mafic sills of dioritic to gabbroic composition show little or no magnetic response in outcrop, probably because the magnetite content in the sills was reduced by chemical processes related to interaction of hydrothermal fluids with cooling magmas of the intrusions.

Evidence from the magnetic and gravity anomaly data suggests that the Cabinet Mountains Wilderness is underlain by a major batholith of felsic composition that extends from north of the Dry Creek stock south almost to the Vermilion River stock. Along this trend are a number of small high-amplitude positive anomalies of 60–100 nT in areas of outcrops of the Wallace Formation of the Belt Supergroup and, in a few cases, the Ravalli Group. In the case of the Ravalli rocks, the highs probably are not related to outcrops of magnetite-bearing Ravalli group rocks that in other places cause linear magnetic highs along ridge tops; instead, because of their equidimensional shape on the map, they may indicate near-surface sources related to granitic intrusions or cupolas of a larger batholith mass at a few kilometers depth beneath the Cabinet Mountains Wilderness.

A basal surface of detachment is inferred from a series of seismic reflections. Depth to the basal surface is 9–18 km, and this surface dips about 15° in inferred crystalline basement rocks. Strong reflections at and below 4 seconds are attributed to stratification in the basement such as layered gneiss or mylonite along the detachment zone for the older tectonic folding. No seismic reflection is present for the Belt-crystalline basement contact. Just below the Pinkham thrust fault, strong reflections attributed to stratification in crystalline basement rocks image relief in the basement on the western flank of the Purcell anticline.

Interpretation of the magnetotelluric data suggests a thick conductive section that is incompatible with a crystalline basement composed of granitic gneiss, mafic intrusive rocks, and high-grade metasedimentary rocks considered typical for the region. Thus, there are major differences between the deep crustal model developed from the magnetotelluric data and the model obtained from the gravity and seismic data. This heterogeneous type of crust is generally not low in resistivity unless partial melting has occurred. Low resistivities may be possible in granitic rocks at depths of 10–15 km and temperatures of 500°C–600°C if 1–3 percent free water is present; however, there is no evidence in the study area for these levels of temperature. A thermally related basement conductive zone could possibly be present now at depth where a low-resistivity (3–5

ohm-m) zone forms the bottom layer in the western part of the magnetotelluric profile. This zone corresponds approximately with the interpreted basal surface of detachment that separates basement rocks from the Prichard Formation of the Belt Supergroup. Some of the low resistivities observed likely are caused by pre-Prichard crystalline rocks (metamorphic (metasedimentary) or igneous) that are conductive because they contain large amounts of metallic minerals. The striking variations in observed resistivities in the Prichard Formation of from 0.6 to more than 400 ohm-meters probably reflect the percentage and continuity of iron-sulfide-rich zones. Another possible line of thermal evidence is the absence of magnetic sources in pre-Belt crystalline rocks at depths of 10–15 km. The lack of magnetic anomalies may relate to shallow Curie-point temperatures, above which magnetism does not exist.

The magnetotelluric data have limitations in structural analysis because resistivities are mostly controlled by the percentages of metallic minerals and not by lithology. Accuracy of the interfaces obtained from the magnetotelluric data is not great, both because of the widely spaced sounding locations and because of the very large contrasts in resistivity between unmineralized and mineralized zones in the Belt Supergroup.

INTRODUCTION

Regional geophysical studies conducted by the U.S. Geological Survey in the northern Rocky Mountains during the past 25 years provide new insights about the geologic framework and mineral resources of the region. In this report, the emphasis is on interpretation of geophysical data compiled for the Libby thrust belt in northwestern Montana (fig. 1). Interpretations complement the results of geologic mapping described by Harrison and Cressman (1993), who also discussed the geology and structural framework of the Libby thrust belt. During the course of their studies, Harrison and Cressman constructed geologic cross sections across the Libby thrust belt on the basis of measured sections and projections of surface geology. Depth cutoff of these sections was 4.3 km (14,000 ft) below sea level.

In the study described herein modeling of gravity anomaly data was done along two of the geologic cross sections to provide information about structure and lithology of the Purcell anticlinorium and Sylvanite anticline from depths greater than 4.3 km to at least as deep as Precambrian crystalline basement in the middle part of the crust. No magnetic modeling was done because of the absence of magnetic anomalies having sources likely in deeply buried crystalline basement.

Included in this report are sections on interpretation of seismic and magnetotelluric data. J.E. Harrison describes interpretations of data from about 70 km of COCORP (The Consortium for Continental Reflection Profiling) seismic

reflection surveying along two profiles that cross the Sylvanite anticline and Purcell anticlinorium. W.D. Stanley describes analysis of five magnetotelluric soundings along a profile that extends across the Libby thrust belt and the Purcell anticlinorium. The lines of section of the gravity models and the COCORP profiles and the locations of the magnetotelluric soundings are shown in figure 2. Data from 13 audiomagnetotelluric soundings in two profiles on the Sylvanite anticline provide information about resistivities of rocks in the upper few kilometers of the crust (Long, 1988).

The geology shown on plate 1 is a simplified version of the 1:125,000-scale geologic map compiled by Harrison and Cressman (1993). The western parts of geologic maps for the Wallace and Kalispell 1°×2° quadrangles (Harrison and others, 1986, 1992) provide the regional geologic context of the Libby thrust belt.

Magnetic and gravity anomaly data are also shown on plate 1. To provide a broader perspective of the geophysical setting, magnetic and gravity anomaly maps (pl. 2) were compiled at a scale of 1:500,000 for the Libby thrust belt and adjacent areas, extending from near lat 47°20' N. to lat 49°00' N. and from near long 114°45' W. to long 116°15' W.

Previous studies of gravity and magnetic anomaly data applied to geologic framework and mineral resource investigations of the region are described in King and others (1970), Harrison and others (1972, 1980, 1985), Kleinkopf and others (1972, 1982, 1988), Wynn and others (1977), Kleinkopf (1977, 1981, 1983, 1984), Kleinkopf and Long (1979), Kleinkopf and Wilson (1981), Kleinkopf and Bankey (1982), Kleinkopf and Harrison (1982), Fountain and McDonough (1984), and Harris (1985).

The author thanks the many U.S. Geological Survey colleagues who contributed to this project. Jack Harrison offered many constructive suggestions and provided many stimulating discussions during various phases of the project and report preparation. The sections on seismic and magnetotelluric investigations by Jack Harrison and Dal Stanley provide substantive contributions to the conclusions of this paper. The geology was digitized and compiled under supervision of Stanton H. Moll; the geologic map of plate 1 was completed in final digital form by Nancy Shock. Viki Bankey and Mike Brickey collected gravity data in the field. Viki Bankey compiled and edited the gravity and magnetic data and prepared early versions of the gravity and magnetic anomaly maps, and Gerda Abrams prepared later versions of the gravity and magnetic anomaly maps used in this report. Several colleagues offered valuable constructive comments during the technical review process.

GEOLOGY

The Libby thrust belt (fig. 1) is in the northwestern part of the Belt basin, which formed along the western edge of the

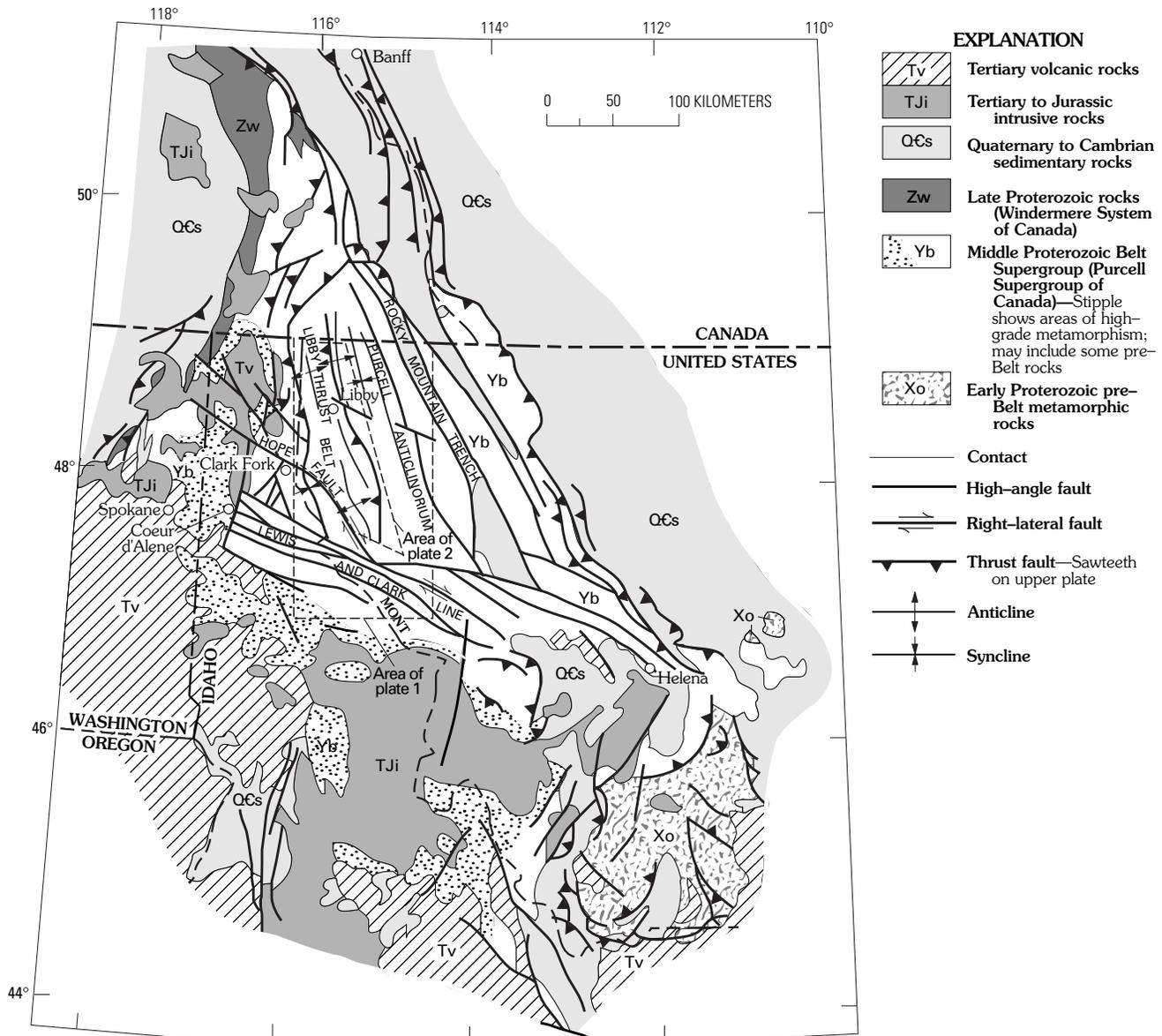


Figure 1. Map showing generalized geology of the Belt terrane in the region of the Libby thrust belt, northwestern Montana and surrounding area. Modified from King (1969) and Harrison and Cressman (1993).

North American craton in Middle Proterozoic time (Harrison, 1972; Harrison and Cressman, 1993). The Belt terrane is the oldest of a series of tectonostratigraphic assemblages that make up a wedge of supracrustal rocks along the western edge of the continental craton (Price, 1981). The Libby thrust belt is one of a series of major north-northwest-trending structural features north of the Lewis and Clark line, a major intraplate tectonic boundary (Reynolds and Kleinkopf, 1977). The Libby thrust belt was characterized by Harrison and Cressman (1993) as a “ripped-apart syncline between two anticlinal structures,” between the Purcell anticlinorium to the east and the Sylanite anticline to the northwest. The Moyie thrust system is along the

western and northwestern margin of the Libby thrust belt and overrides it on the southwest (Harrison and Cressman, 1993). The thrust belt is limited to the south by the Hope fault (fig. 1), which Harrison and Cressman described as a “crustal flaw.”

Some 15 km of Middle Proterozoic Belt Supergroup rocks underlies the Libby thrust belt. Rocks of the Belt Supergroup grade upward from turbidites through marginal-marine, tidal-flat, and shallow-shelf deposits. The sequence consists mostly of fine-grained sedimentary rocks, mainly argillite, siltite, quartzite, and carbonate. The Pri-chard Formation, the oldest of the Belt units, is dominantly quartzite but contains beds of pyritic-pyrrhotitic argillite,

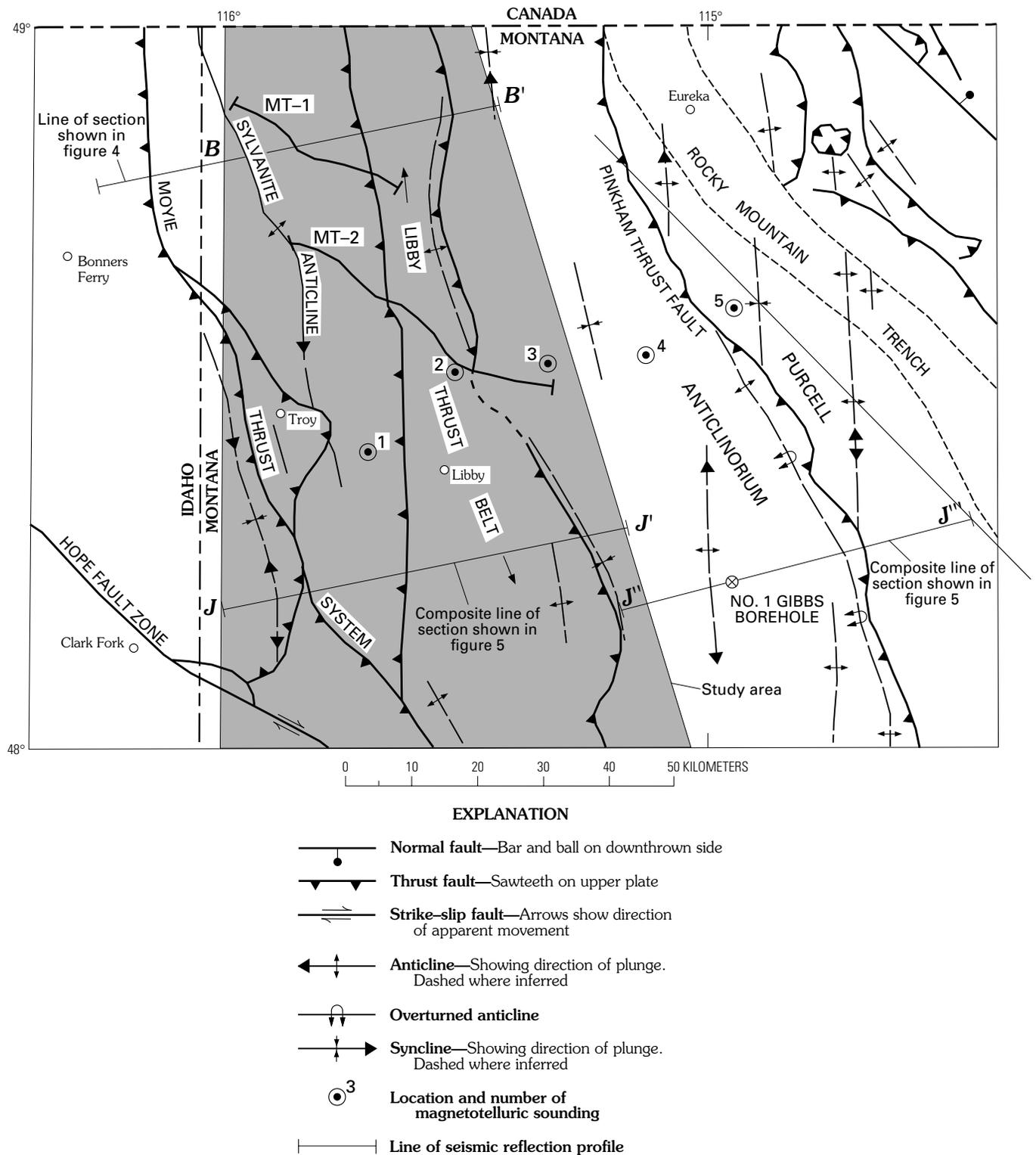


Figure 2. Map showing major structural features in the area of the Libby thrust belt, northwestern Montana. Lines of extended geologic cross sections B-B' and J-J' (Harrison and Cressman, 1993) used in gravity modeling, lines of seismic reflection profiles MT-1 and MT-2, and locations of magnetotelluric soundings 1 through 5 and Gibbs No. 1 borehole are also shown.

which is more dense than overlying rocks of the Ravalli Group. The thickest exposures of Prichard rocks in the map area are in the Sylvanite anticline, west of Yaak (pl. 1A), where some 5.6 km of Prichard rocks is exposed (Harrison and Cressman, 1993). Almost 1,000 m of mafic sills is recorded in measured sections in the Yaak area. Successively overlying the Prichard Formation are the Ravalli Group, the Helena and Wallace Formations, and the Missoula Group.

A number of short-wavelength positive magnetic anomalies (pl. 1A) are associated with outcropping metasedimentary rocks of the Burke and Revett Formations of the lower part of the Ravalli Group. In hand specimen, particularly those of the Burke Formation, euhedral grains of magnetite were observed in siltite (Kleinkopf and others, 1972). The overlying Wallace Formation consists mainly of calcareous and dolomitic fine- to medium-grained clastic rocks. Above the Wallace Formation is the Missoula Group, which consists primarily of interbedded red and green clastic rocks that are less dense than other Belt rocks. Rocks of the Missoula Group produce negative gravity anomalies where thick sequences are juxtaposed against denser Belt rocks. Only minor amounts of Cambrian sedimentary rocks are preserved in outcrop, and no other Phanerozoic sedimentary rocks are present in the study area except for alluvial, lake-bed, and glacial deposits and other low-density sediments of Pleistocene to Holocene age that have accumulated in modern stream valleys.

Rocks of the Belt Supergroup exhibit an increase in metamorphic grade from east to west across the basin and with depth in the stratigraphic section. Metamorphic grade ranges from the biotite zone of the greenschist facies in the lowest exposed part of the Prichard Formation through chlorite-sericite rocks in middle Belt to high-grade diagenesis at the top of the Belt Supergroup (Harrison and Cressman, 1993). Because the sedimentary rocks are mostly argillite and siltite, the average rock density generally increases downsection with depth and with increased metamorphic grade. Exceptions are rocks of carbonate sequences of the Helena and Wallace Formations, which are more dense than the underlying rocks of the Ravalli Group. Although massive quartzite is present throughout the section, its volume as compared to that of the total section is low, and thus its influence on gravity patterns is minimal.

The Belt sequence in the Libby thrust belt has been intruded by Precambrian sills of diorite to gabbro, early Cretaceous plutons ranging from granite to pyroxenite, and Eocene plutonic rocks of quartz monzonite porphyry to granodiorite. Middle to Late Proterozoic mafic sills are abundant in the lower part of the Prichard Formation and are less abundant in the Ravalli Group, Wallace Formation, and Missoula Group. The best exposures of sills are in cirques, particularly on the Sylvanite anticline, and on ridges (Harrison and Cressman, 1993). The sills are altered (King and others, 1970; Bishop, 1973) and commonly exhibit little or no magnetic expression.

Scattered exposures of Early Cretaceous and Eocene plutonic igneous rocks are present in the study area. These rocks, ranging in composition from granite and granodiorite to syenite and pyroxenite, have been intruded into Belt strata (Harrison and Cressman, 1993). The largest exposed plutons are the Dry Creek stock (unit Kg, pl. 1), about 15 km southwest of Libby in the Cabinet Mountains, and the Vermilion River stock (unit Kg), just east of the town of Trout Creek. Smaller exposures of granitic rocks similar to the rocks of the Dry Creek stock are present a few kilometers north, west, and south of the stock. Mafic intrusive complexes, principally pyroxenite and syenite (unit Kps), are exposed at Vermiculite Mountain, 10 km east-northeast of Libby. At Bobtail Creek, 12 km north of Libby, a pluton of predominantly coarse grained, porphyritic syenite (unit Kps) contains segregations of pyroxene and amphibole.

AEROMAGNETIC ANOMALY DATA

Aeromagnetic anomaly data for the study area were compiled from analog records obtained from two regional aerial surveys flown under contract to the U.S. Geological Survey. The elevation of most of the study area is between 1 and 2 km, and several mountain peaks are higher than 2.3 km. Both surveys were flown east-west at a nominal altitude of 2.1 km above sea level, except to clear the high peaks. The survey north of lat 48°30' N. was flown in 1972 by Scintrex Minerals Inc., at a line spacing of 3.2 km (U.S. Geological Survey, 1973). The survey south of lat 48°30' N. was flown in 1968 by Lockwood, Kessler, and Bartlett, Inc., at a line spacing of 1.6 km (U.S. Geological Survey, 1969a-j; Kleinkopf and others, 1972).

The total-intensity aeromagnetic anomaly data are shown at scales of 1:250,000 and 1:500,000 (pl. 1A, 2A). Plate 1A is a mosaic of the aeromagnetic anomaly maps received from the contractors and is superimposed on a generalized version of the digital geologic map of Harrison and Cressman (1993). The residual total-intensity data were reduced to a single datum, then continued to a common altitude of 2.1 km above sea level and merged by fitting along map boundaries using programs developed by M.W. Webring (written commun., 1981) and R.E. Sweeney (written commun., 1981). The merged data were then gridded at a spacing of 1 km and contoured at an interval of 20 nT (pl. 2A). The International Geomagnetic Reference Field (IGRF) for Epoch 1975 (Peddie and others, 1976), which is about 6.6 gammas per kilometer to the northeast, was removed from the data.

GRAVITY ANOMALY DATA

Gravity data for 775 stations were extracted from regional digital data sets compiled in support of U.S.

Geological Survey programs in geologic framework and mineral resource appraisal. The data originate from a variety of sources including unpublished files of the U.S. Geological Survey, Wynn and others (1977), Kleinkopf (1981), Kleinkopf and Wilson (1981), Bankey and others (1985), and a U.S. Department of Defense, Defense Mapping Agency (DMA), data base (written commun., 1989). Measurements were made with high-sensitivity gravity meters using four-wheel-drive vehicles and, in some cases, foot traverses (Bankey and others, 1982, 1985; Brickley and others, 1980). The station spacing is variable, ranging from 2–3 km along roads to greater than 5 km in roadless areas.

Gravity observations were made at locations of known, or recoverable, horizontal and vertical positions in terms of longitude, latitude, and elevations. These positions include survey bench marks, photogrammetric elevation points shown on U.S. Geological Survey 7.5- and 15-minute topographic maps, and locations of low topographic relief at which elevations and horizontal positions could be estimated with confidence. The observed gravity is referenced to the IGSN-71 (International Gravity Standardization Net) datum (Morelli and others, 1974) by means of ties to U.S. Department of Defense bases ACIC-0442 at Missoula, Mont., and ACIC-4006-1 at Wallace, Idaho (U.S. Department of Defense, 1974). Gravity reduction procedures are based on equations discussed by Cordell and others (1982). All gravity stations were reduced to the complete Bouguer anomaly, assuming a mean crustal density of 2.67 g/cm³, using the 1967 gravity formula (International Association of Geodesy, 1967). Terrain corrections were made using computer software to access digital terrain files. Terrain corrections were calculated radially around each station to a distance of 166.7 km (Plouff, 1977). The final-processed data, consisting of complete Bouguer gravity anomalies, were gridded and contoured using computer routines based on minimum curvature (Briggs, 1974; Webring, 1981).

GEOLOGIC INTERPRETATION OF AEROMAGNETIC ANOMALIES

The dominant anomaly patterns on the 1:250,000-scale aeromagnetic anomaly map (pl. 1A) consist of equidimensional positive anomalies, short-wavelength positive and negative anomalies elongated generally north to northwest, and zones of steep magnetic gradient. Three types of geologic sources that contain relatively high percentages of magnetite account for most of the anomalies. The sources mainly are in outcrop but in some cases are partly or totally buried in the near-surface. The principal magnetic anomaly sources are igneous intrusive rocks, magnetite-bearing sedimentary rocks of the Ravalli Group, and major fault zones.

The Proterozoic basement, where drilled in western Montana, is primarily a mixture of granite and granitic

gneiss, both of which typically are of low magnetization (Harrison and others, 1972). Long-wavelength anomalies that may have sources in deeply buried crystalline basement rocks at about 15 km are not known to be present in the region (Harrison and others, 1980). The lack of detectable magnetic anomalies in the study area is attributed to the relatively nonmagnetic character of the basement rocks and their deep burial. Resistivities measured at crystalline basement levels may be due to high-temperature crystalline basement rocks (see discussion on magnetotelluric data). Correspondingly, the lack of magnetic anomalies may be ascribed to a crystalline basement complex at depths of 10–15 km that has temperatures above the Curie point, at which magnetization of the rocks is lost. The mafic sills of dioritic to gabbroic composition normally would be expected to be magnetic but show little or no magnetic response in outcrop. This anomalous low magnetization is attributed to reduction of magnetite content in the sills by chemical processes related to interaction between hydrothermal fluids and cooling magma of the intrusions (King and others, 1970; Harrison and others, 1972). Gravity anomaly data, on the other hand, show distinct anomalies that have sources, as determined from modeling, at or near crystalline basement levels.

The most distinctive magnetic anomalies in the principal study area are five positive anomalies (numbered 1, 2, 3, 4, and 5 on pl. 1A) associated with Cretaceous or younger cupolas and stocks that are exposed or are known from drill-holes to be present in the near-surface. These anomalies range in amplitude from 100 to more than 3,000 nT. The magnetic data provide information about the subsurface extent of these igneous intrusions and give clues for locating other buried intrusions that have subtle expressions.

The most prominent of the five magnetic anomalies (anomaly 1, pl. 1A) is associated with a pyroxenite-syenite complex (unit Kps) that is partly exposed at Rainy Creek–Vermiculite Mountain, about 6 km east-northeast of Libby. The anomaly has an amplitude exceeding 3,000 nT, and it correlates with the main mass of ultramafic rocks. Pyroxenite is the principal ultramafic rock, and altered pyroxenite in this stock has been a major source of vermiculite in the United States. Various aspects of the geology of the complex and adjacent areas were studied by Larsen and Pardee (1929), Boettcher (1966), and Harrison and Cressman (1993), who concluded that the complex is a laccolith. The complex consists of a biotitic core surrounded by biotite pyroxenite and an outer ring of magnetite pyroxenite. A large pluton of syenite and associated alkaline syenite dikes are in the southwestern part of the complex. The resulting anomaly is a combined expression of the total complex and does not distinguish syenite from pyroxenite rocks. Larsen and Pardee (1929) reported that the syenite locally contains 3–12 percent magnetite. Boettcher (1966) speculated that minor fenitization of Belt rocks along the northern contact of the complex may indicate a large body of carbonatite at

depth. The Bouguer gravity anomaly data show a residual high resulting from a change in gradient along a nosing in the contours (pl. 1B) that is attributed to mafic rocks of the complex that are denser than the enclosing rocks. The residual gravity high correlates with the positive magnetic anomaly over outcrops of the complex.

Northwest of the Rainy Creek complex, about 8 km north-northwest of Libby, a pluton (unit Ks, pl. 1) crops out in two places near Bobtail Creek. The associated single positive magnetic anomaly (anomaly 2, pl. 1A) has an amplitude of 900 nT and is slightly elongated north-northwest. The pluton is mainly syenite and includes segregations of pyroxene and amphibole (Gibson, 1948). A high nosing in the gravity contours correlates with the positive magnetic anomaly over the complex in much the same character as at anomaly 1. Both the Rainy Creek and Bobtail Creek complexes are estimated to be about 100 m.y. old (Harrison and Cressman, 1993). A northwest-trending belt of high gradient in the Bouguer gravity anomaly data suggests that the two features may be connected in the subsurface, possibly along a northwest-trending structural zone, although no surface indication of such a zone is evident in the geologic mapping. Boettcher (1966) stated that the syenite and ultramafic rocks at Bobtail Creek and Rainy Creek may be comagmatic.

A low-amplitude positive magnetic platform extends to the south of anomaly 1 across the Kootenai River for some 15 km in the form of a wide plunging nose in the magnetic contours (pl. 1A). A small, but distinct nose is superimposed on the magnetic platform anomaly (pl. 2A) near Fisher Mountain. The anomaly sources may be a shallow cupola and a large related mass of moderately magnetic rock that gives rise to the platform anomaly.

In the southwestern part of the map, just east of Trout Creek, a positive magnetic anomaly (anomaly 3, pl. 1A) of almost 300 nT is associated with outcrops of hornblende granodiorite (unit Kg) of the Vermilion River stock. The axis of the anomaly is oriented north-northeast and is offset toward the northwest edge of the outcrops. Intrusive rocks probably are present in the subsurface beneath lower Prichard rocks that crop out northwest of the outcrops of the stock. The associated broad gravity high reflects the high-density hornblende granodiorite rocks that are in contact with rocks of the lower part of the Prichard Formation.

Near the southern end of the Libby thrust belt study area and just northeast of Thompson Falls, a circular positive anomaly (anomaly 4, pl. 1A) of more than 200 nT amplitude indicates the presence of a buried intrusion. According to drill-core information provided by the staff of Noranda Exploration, Inc. (unpub. data, 1979), quartz monzonite porphyry is present about 775 m below the ground surface (Kleinkopf and others, 1988). The configuration of the anomaly and the horizontal extent of the steepest gradient on the flanks of the anomaly are consistent with depth of burial as indicated by the core-hole information. Using potassium-argon techniques, analysis of biotite and

potassium feldspar from the quartz monzonite gave radiometric ages of 40–50 Ma (Marvin and others, 1984), younger than ages for the major intrusions to the north. An associated gravity low is discussed in the section on interpretation of the gravity anomaly data.

Another well-exposed intrusive complex, the Dry Creek stock, about 15 km southwest of Libby, has less prominent magnetic expression (anomaly 5, pl. 1A). The expression is composite and consists of three small positive anomalies of less than 100 nT in areas of granitic outcrops in high elevations of the eastern part of the stock. To the west, magnetic gradients decrease rapidly, and there is no anomaly over exposures of the stock (Kleinkopf, 1981). The lithology of the Dry Creek stock is quartz monzonite to granodiorite (Gibson, 1948), and the granitic rock here probably belongs to a 100-m.y.-old intrusive event (Marvin and others, 1984; Harrison and Cressman, 1993). The complex character of the magnetic response of the Dry Creek stock is strikingly different than the distinct 300-nT positive anomalies associated with the Vermilion River and Liver Peak stocks. Magnetic susceptibilities of three samples of granodiorite from the eastern part of the Dry Creek complex range from 0.019 to 0.072 International System (SI) units (Kleinkopf, 1981) and generally correlate with topographic highs. The magnetic highs may relate to small stocks that formed as apophyses of the larger, relatively less magnetic granitic complex of the Dry Creek stock. Harrison and Cressman, 1993) reported that all stocks and plutons in the map area have contact metamorphic aureoles. In particular, the Dry Creek stock has a 1,000-m-wide hornfels zone where it intrudes rocks of the Wallace Formation and Missoula Group. The stock is sheared and foliated by faulting, particularly on the west side (Wells and others, 1981) where the magnetic map shows little or no magnetic expression. I infer from the lack of magnetic expression that little primary magnetite was present in the intrusion. Gibson (1948) reported no alteration of the stock but observed that magnetite formed after initial crystallization of the magma and probably is interstitial to pyroxene and other minerals. A small outcrop of granodiorite is about 12 km south of the Dry Creek stock (pl. 1A). No magnetic anomaly was detected on two flight lines that passed just to the north and to the south of this outcrop, which further indicates that the granodiorite is of low magnetization (Kleinkopf, 1981).

Many of the elongated short-wavelength magnetic anomalies are related to magnetite-rich horizons predominantly in siltite layers of the Burke and Revett Formations of the Ravalli Group (Kleinkopf and others, 1972). These anomalies are typically 50–100 nT in amplitude, and many are elongated north-northwest along outcrops of Ravalli Group rocks that are topographically high and, in some cases, structurally controlled. Field checks in the east-central part of the area show that positive anomalies are associated mainly with outcrops of the Burke Formation. Hand specimens of the Burke exhibit abundant euhedral magnetite

grains. Magnetic susceptibilities for three samples collected in this area of from 0.013 to 0.035 SI units can account for the observed anomalies. In the northern part of the area at Mount Henry, and just to the south, two distinct positive anomalies correlate with outcrops of Revett Formation in high topography (Bankey and others, 1986).

The Hope fault zone and faults of the Lewis and Clark line are expressed by parallel magnetic alignments (pl. 2A). The Hope fault is along the southwestern margin of the Libby thrust belt and is delineated in the magnetic anomaly data by zones of steep gradients approximately parallel with the fault (pl. 1A). In general, the magnetic patterns are more variable on the northeastern side of the fault (Kleinkopf and others, 1972).

Southwest of the Libby thrust belt, the magnetic anomaly data show expressions of igneous intrusions and fault zones. A few kilometers north of Wallace, Idaho, the regional aeromagnetic anomaly map (pl. 2A) shows a north-northeast-elongated, 200–300-nT, positive anomaly that correlates with quartz monzonite exposures of the Gem stock intrusive complex (Hobbs and others, 1965; Kleinkopf and others, 1988). Also in the Wallace area, distinct west-northwest linear magnetic trends reflect structural alignments of the Thompson Pass, Osburn, and Placer Creek faults, which are part of the Lewis and Clark line (Kleinkopf and others, 1988). A large, complex positive magnetic anomaly 25 km west of Thompson Falls correlates with outcrops of granitic intrusions (unit Ks) that are composed of syenite. The elongate shape of the anomaly suggests that granitic rocks are present as an extension of, or possibly as a separate, pluton in the subsurface southwest of the outcrop.

GEOLOGIC INTERPRETATION OF BOUGUER GRAVITY ANOMALIES

In the area of the Libby thrust belt, there is a strong correlation of gravity anomalies with both geologic framework and major lithologic units. The geology and principal structural features are shown, together with the Bouguer gravity anomaly, to illustrate the gravity signatures and to provide a reference for discussions of the geologic interpretations of the gravity anomaly data (pls. 1B, 2B). The regional gravity field dips gently to the east across the study area and exhibits a complex of regional-scale positive and negative anomalies that correspond to broad open folds west of the Rocky Mountain trench (Harrison and others, 1980).

The gravity anomaly patterns can be discussed in terms of configurations of the –130- to –140-mGal contours (pls. 1B, 2B). In the middle and southern parts of the study area, structurally deformed rocks of the Missoula Group generally are less dense than less deformed adjacent rocks of older parts of the Belt Supergroup. The –140-mGal contour delimits a broad negative area whose source is attributed to

low-density Missoula Group rocks that also have experienced some reduction in density due to faulting and fracturing associated with development of the Libby thrust belt. Much of the grain of the gravity anomaly patterns within the broad negative area is approximately parallel with the strike of thrust and normal faults of the Libby thrust belt (pls. 1B, 2B). The broad negative gravity feature has its lowest value of –160 mGal just east of Thompson Falls, where it is approximately coincident with the Liver Peak magnetic anomaly (anomaly 4, pl. 1A). This deep gravity low (–160 mGal) forms the southern part of a horseshoe-shaped negative anomaly that is open to the north and has residual lows at both ends of the horseshoe. The distinct low (–160 mGal) centered on the south flank of Liver Peak may reflect low-density felsic rocks of the intrusion. In addition, the deepest part of the gravity low may relate to low-density hydrothermally altered rocks associated with molybdenum-tungsten-mineralized rock at Liver Peak. The west and northwest extension of the horseshoe anomaly may reflect a structural trough of low-density Quaternary sediments and localized fracturing of Belt rocks at the intersection of the Hope fault and south-trending thrust faults of the Libby thrust belt. Alternatively, a less magnetic phase of low-density intrusive rocks at Liver Peak may be extensive in the subsurface in the west and northwest areas.

North of lat 48° N., about 25 km northeast of Trout Creek, the regional gravity low defined by the –140-mGal contour narrows and follows the north- to northeast-trending Fisher River where it cuts around geologic structure. The low gravity values may express crossfaulting that controls the river direction here. Northwest of the river, a northeast-trending gravity divide is defined by –140-mGal contours. Northwest of the divide, gravity values decrease to less than –144 mGal over the alluvial valley south of Libby, which is in the center of a broad, relatively flat bottomed low approximately defined by the –130- to –140-mGal contours. Assuming that about 6 mGal of relief is associated with the alluvial valley, the thickness of valley fill may exceed 400 m.

North of Libby, north-northwest gravity trends correlate with major thrust faults of the Libby thrust belt as it passes north into Canada. The broad, but distinct north-trending gravity low that extends south of Yaak separates the well-defined gravity highs associated with the Purcell anticlinorium on the east and the Sylvanite anticline on the west.

The Sylvanite anticline and the Purcell anticlinorium exhibit prominent gravity highs that have amplitudes exceeding 10 and 20 mGal, respectively (pls. 1B, 2B). The high associated with the Purcell anticlinorium generally trends northwesterly; however, on close inspection, gravity patterns show that the broad high is composed of three separate northerly trending highs arranged en echelon along a northwest trend. The small anticlinal axis passing just west of the Gibbs No. 1 drillhole correlates with the southernmost gravity high. The gravity high associated with the Purcell

anticlinorium is broken and offset at a location about 10 km east of Libby. The offset is part of a west-northwest trend in the gravity anomaly data that passes just north of Libby and extends to the Moyie thrust fault near Troy. In addition, discontinuous trends in the magnetic anomaly data correlate with the gravity trends, notably just south of the Rainey Creek intrusive complex (anomaly 1, pl. 1A). The composite gravity high associated with the Sylvanite anticline exhibits a distinct northerly trend and subtle, superimposed northwesterly trends. The mapped axis of the anticline is offset southwest of the axis of the gravity high. Gravity modeling, discussed in the next section of this paper, indicates that the Purcell anticlinorium and the Sylvanite anticline are very likely cored by stacks of thrust slices of dense crystalline basement rocks that account for the large gravity highs across these two structures.

West of the Cabinet Mountain Wilderness, the Moyie thrust fault is along the west side of a narrow troughlike gravity anomaly related to the north-trending Bull River valley (pl. 2B). At the north end of the valley, the thrust turns and follows the northwest extension of the gravity trough into Idaho. The deepest part of the trough is about 10 km northwest of Troy. Three distinct lows are along the trough associated with Bull River valley. The deepest low, which exceeds 6 mGal amplitude, is at the north end of the valley, an area of complex geologic structure (pl. 1B). This deep low is separated from the next low to the south by an east-northeast-trending gravity ridge. Contour alignments and trend projection across the Cabinet Mountain Wilderness provides some evidence that the ridge may express a buried fault zone that extends northeast as far as the gravity platform just north of Libby. Although no continuous fault zone has been mapped in the surface geology, the geologic map shows discontinuous northeast-trending faults and areas of fault intersection along the projected gravity feature.

In the Cabinet Mountains Wilderness, in the central part of the Libby thrust belt, a line of positive gravity anomalies, uniformly about 6–10 mGal amplitude above background, extends south-southeast from near the Kootenai River to as far as the latitude of Trout Creek. One of the highs is centered north of the exposures of the Dry Creek stock about 15 km southwest of Libby but is much more extensive than either outcrops of the stock or the associated magnetic anomalies described earlier in this report as well as in Kleinkopf (1981). The second gravity high is at Snowshoe Peak, and a possible correlative magnetic source is in the subsurface beneath outcrops of the Wallace and Helena Formations and the Ravalli Group. The third gravity high is at Flat Top Mountain, about 20 km south-southeast of the second; the highest part of this anomaly is about 5 km west of Flat Top Mountain. Between the second and third highs, the south-southeast trend of the highs is broken by a discontinuous zone of gravity patterns that trend east-northeast toward Fisher Mountain; crosscutting gravity contour alignments are along the east-northeast trend. In addition, both in the

Cabinet Mountains Wilderness and in the main part of the Libby thrust belt, structural complexities and crossfaulting are present along the trend (pl. 1). The anomalous gravity and the structural features may reflect a zone of weakness in the crust of unknown origin. The fourth gravity high is about 16 km south-southeast at Trout Creek and correlates with the Vermilion Creek stock of hornblende granodiorite composition. Kleinkopf (1981) concluded from interpretations of the gravity high over the Dry Creek stock and from the distribution of the magnetic anomalies that the Cabinet Mountains Wilderness may be underlain by an extensive granitic batholith that is relatively nonmagnetic. The gravity highs may reflect large near-surface intrusions along the feature, and the small positive magnetic anomalies may indicate near-surface sources associated with small granitic intrusions or cupolas that may be apophyses of a possible batholithic mass at a depth of a few kilometers, as suggested by the gravity model along geologic section *J–J'* (fig. 5) (see following section). On the basis of surface mapping and indications in the outcropping sedimentary rocks, Harrison and Cressman (1993), in their structure sections, showed the Dry Creek stock extending to the south.

GEOPHYSICAL INTERPRETATION OF DEEP-SEATED GEOLOGIC FEATURES

MODELING OF GRAVITY PROFILES

Modeling of Bouguer gravity anomaly data for the Libby thrust belt and adjacent areas supports the interpretation that the crystalline basement is elevated beneath the Purcell anticlinorium and the Sylvanite anticline. The model studies update previous model studies of the Purcell anticlinorium by myself, described in Harrison and others (1980), by addition of new gravity control along the sections and new subsurface lithologic information obtained from well logs in the Atlantic Richfield–Marathon Oil Gibbs No. 1 borehole, NE $\frac{1}{4}$ sec. 2, T. 28 N., R. 27 W. (pl. 2). An important constraint on the validity of the modeling is selection of reasonable densities for the major rock types, or combinations of rock types, depicted in the geologic cross sections. These rock types include crystalline basement, presumed to be Proterozoic in age, Prichard Formation and sills, and post-Prichard strata composed mainly of rocks of the Ravalli Group, Helena and Wallace Formations, and Missoula Group. I selected values for density based on laboratory measurements and on supporting evidence from well logs taken in the Gibbs No. 1 deep borehole (fig. 3).

Densities for a given rock unit within the study area are assumed, on the basis of the general regional consistency of rock types, to be laterally uniform. In laboratory measurements of metamorphic rocks, Smithson (1971) found a density range from 2.7 g/cm³ for granitic gneiss to 2.86 g/cm³

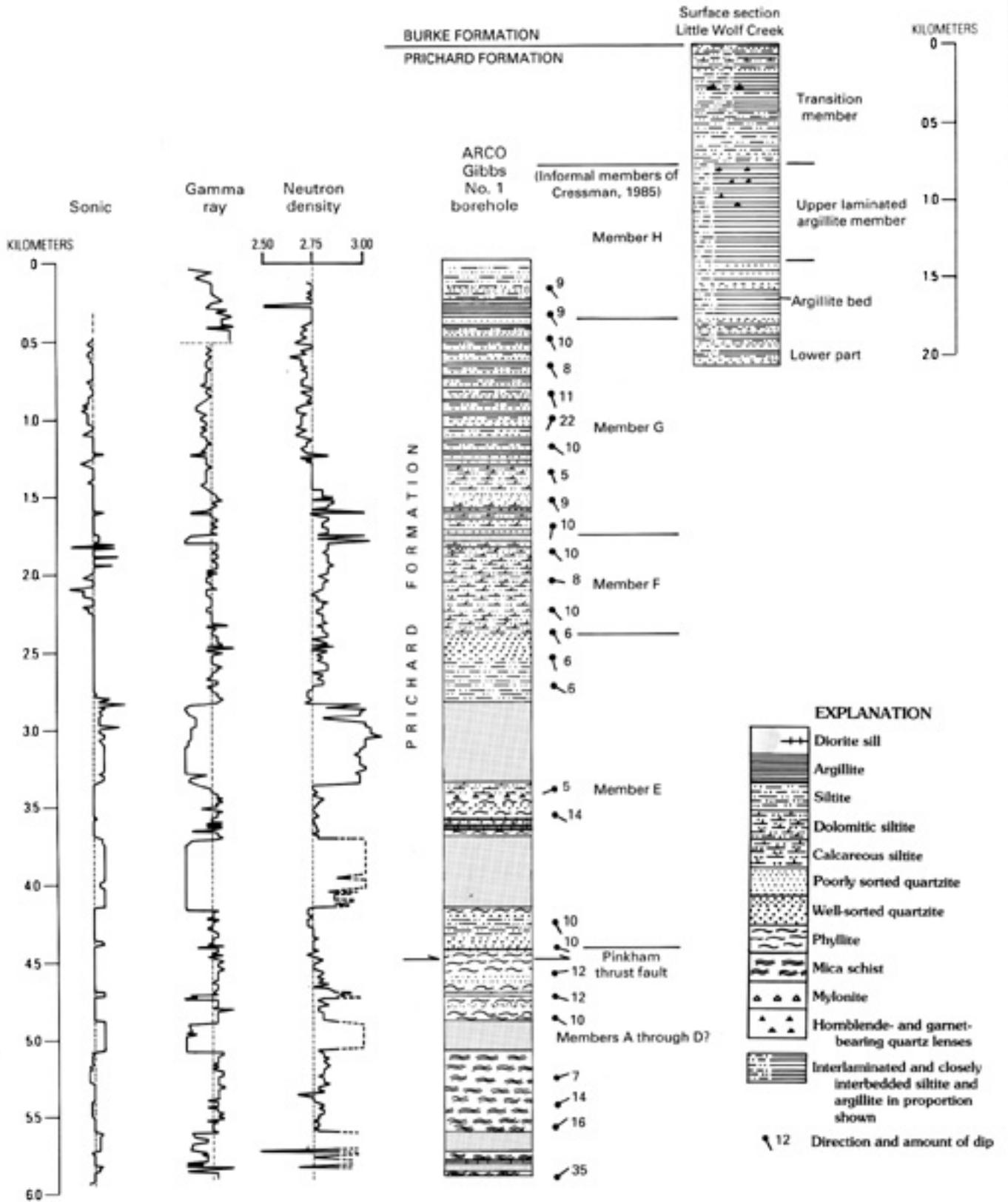


Figure 3. Generalized lithologic and geophysical logs, Gibbs No.1 borehole, Flathead County, Montana. Neutron density log is in grams per centimeter per second per second. Data courtesy of Atlantic Richfield and Marathon Oil Companies. Surface section at Little Wolf Creek is also shown. Modified from Harrison and Cressman (1993).

for granulite facies. I used 2.8 g/cm^3 as a reasonable estimate for the density of the crystalline basement. Density values for 13 samples of post-Prichard Belt rocks (measured in USGS laboratories) range from 2.58 to 2.76 g/cm^3 and average 2.67 g/cm^3 . Earlier laboratory measurements of Precambrian mafic sill samples yielded an average density value of 2.91 g/cm^3 (Harrison and others, 1972). The Precambrian sills in the borehole (fig. 3) are characterized by high density, low radioactivity, and rather high velocity (Harrison and others, 1985). The neutron-density log shows considerable variation in density of the sills, presumably related to alteration. Density values range from about 2.76 g/cm^3 to spikes on the log exceeding 3.0 g/cm^3 . The information from these logs, together with data from the lithologic log, provides reliable thickness estimates for the sills, which total more than 1,000 m of the drilled rock. I estimated that 7.6 km or more of Prichard Formation underlies the borehole site. The assumption was made that the density of the Prichard Formation, without sills, is in the range of from 2.65 to 2.70 g/cm^3 , considering the thick sequences of quartzite and argillite. Thus, combining these values with an average value of about 2.91 g/cm^3 for the Precambrian sills, I obtained an average density for the total column of Prichard Formation and sills of about 2.73 g/cm^3 . The lithologic units and corresponding densities assigned to the bodies are listed in table 1.

Gravity models were calculated along the two lines of section, $B-B'$ and $J-J''$ prepared by Harrison (Harrison and Cressman, 1993), in an attempt to gain information about structure and lithology along the zone of detachment and at crystalline basement levels at depths of approximately 15 km. The sections were simplified and extended laterally (figs. 4, 5) for purposes of the gravity modeling. Geologic data in Idaho used to extend section $B-B'$ are from a geologic map of the Eastport area (Burmester, 1985). The expansion of section $J-J'$ in Montana is from new mapping by Harrison (Harrison and others, 1992); the extension of section $J''-J'''$ is offset 13 km southward along strike in order to cross the Purcell anticlinorium at the location of the Gibbs No. 1 borehole (fig. 2). Two-dimensional modeling of the gravity data was done on a mainframe computer using the software SAKI (Webring, 1982). Control for the modeled sections was provided by random-spaced gravity stations that are along or projected into the lines of section. The resulting gravity control along the modeled sections varies from 1 to more than 5 km in spacing of stations.

The Purcell anticlinorium and the Sylvania anticline are appropriate for gravity model studies. Both structures exhibit prominent positive gravity anomalies that correlate with geologic structures at the surface. The gravity anomaly across the Sylvania anticline is well defined and is as much as about 10 mGal in amplitude. The gravity expression associated with the Purcell anticlinorium has an amplitude of 15–20 mGal, and the anticlinorium is more than 50 km wide and is remarkably continuous and linear for about 100 km to the north into Canada. Several theories on source and mass

Table 1. Lithologies and densities assumed for gravity models of extended geologic sections $B-B'$ and $J-J'$, Libby thrust belt, northwestern Montana. [See text for explanation. Lines of section are shown in figure 2; geologic sections and gravity models are shown in figures 4 and 5]

Body	Density (g/cm^3)	Lithology
Model $B-B'$ extended		
1	2.80	Crystalline basement.
2	2.73	Mafic sill complex.
3	2.73	Prichard Formation and sills.
4	2.68	Ravalli Group.
5	2.70	Ravalli Group.
6	2.70	Ravalli Group and Helena and Wallace Formations.
7	2.80	Crystalline basement.
Model $J-J'$ (extended $J''-J'''$)		
1	2.80	Precambrian crystalline basement.
2	2.73	Cretaceous pluton of quartz monzonite porphyry.
3	2.73	Prichard Formation and sills.
4	2.73	Prichard Formation and sills.
5	2.67	Mainly Ravalli Group, Wallace Formation, and Missoula Group.
6	2.75	Mainly altered Wallace Formation and Missoula Group.
7	2.69	Mainly Ravalli Group, Wallace Formation, and Missoula Group.
8	2.64	Ravalli Group.
9	2.79	Ravalli Group and Prichard Formation.

distribution have been suggested to account for the prominent gravity high associated with the Purcell anticlinorium. In a study of electrical conductivity and gravity data, I (in Wynn and others, 1977) modeled the anomaly as a basement uplift interpreted as the result of movement of major fault blocks. In a later study, Harrison and others (1980) concluded that the source of the anomaly beneath the Purcell anticlinorium is not a vertical uplift but very likely is a stack of thrust slices of high-density crystalline basement rocks that are elevated above the regional basement surface. During the early 1980's, a popular theory favored among various petroleum explorationists attributed the source of the Purcell anomaly to high-density lower Paleozoic carbonate rocks that would provide attractive exploration targets. In a regional structural analysis, Fountain and McDonough (1984) postulated that the anomaly is caused by a high-density body in the form of a basement ramp anticline beneath the Purcell anticlinorium. Harris (1985) modeled the Purcell gravity anomaly and attributed the source of the anomaly to mafic sills in the lower part of the Prichard Formation above a uniformly dipping crystalline basement surface. In this report, I refine, on the basis of further analysis and studies of the data, earlier interpretations in which the source of the

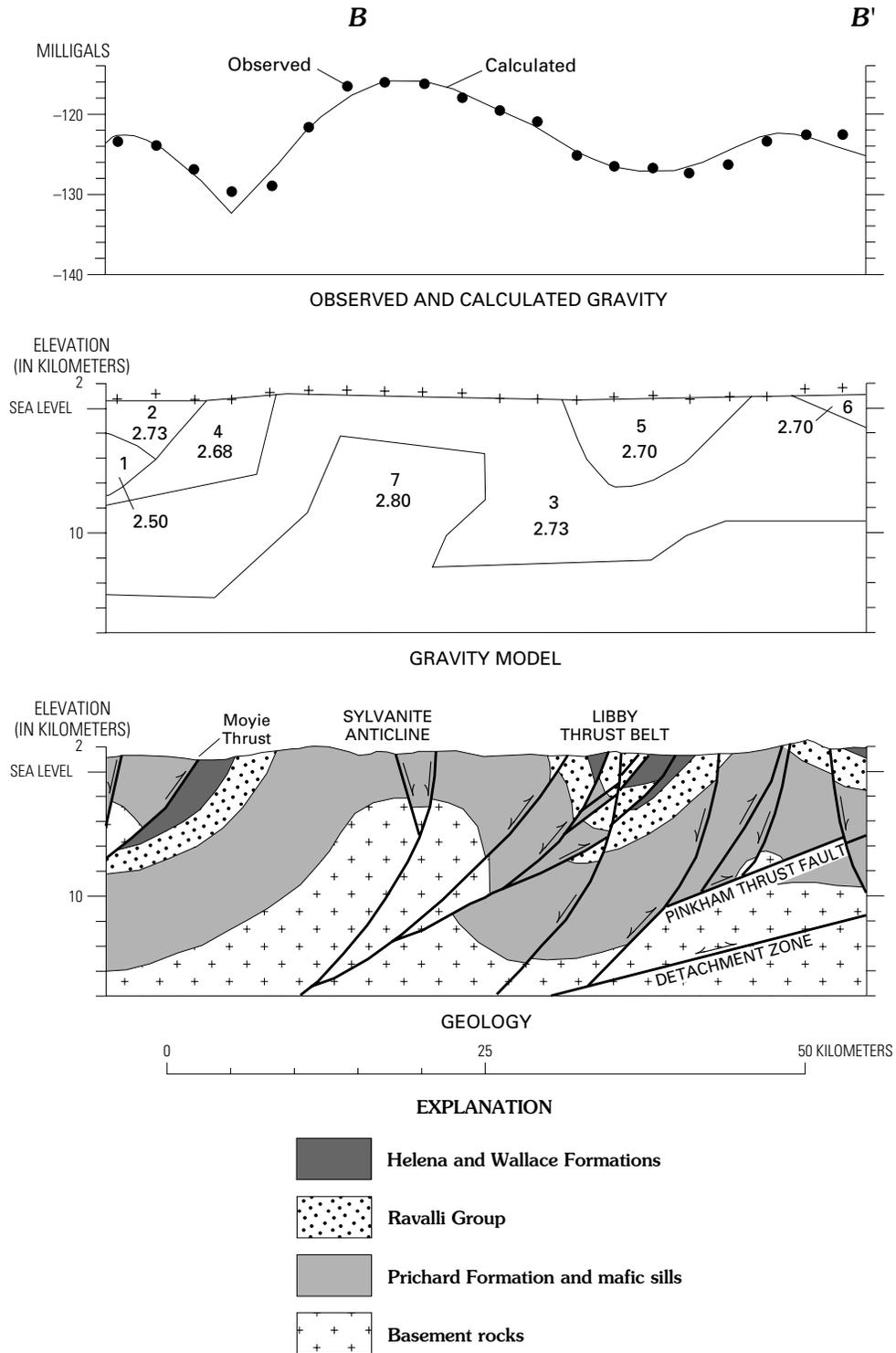


Figure 4. Gravity block model of extended geologic cross section *B-B'* showing inferred lithology and structure beneath the Sylvania anticline and northwestern part of the Purcell anticlinorium, Libby thrust belt, northwestern Montana. Numbers on gravity model refer to body number and assumed density (in grams per cubic centimeter) as shown in table 1; for example, for body 2, the density is 2.73 g/cm³.

anomalies is thrust slices of dense crystalline basement rocks that core the Purcell anticlinorium.

DEEP FOLDS AND FAULTS INTERPRETED FROM SEISMIC DATA

By Jack E. Harrison

Seismic data support the interpretation of crystalline basement beneath Prichard as shown in figure 6. The seismic data identify the mafic sills, which are excellent seismic reflectors (fig. 3), and the sills clearly mimic surface structure to depths of about 8 km below ground level at which seismic data lose definition (Harrison and others, 1985). Seismic data were collected by others who discussed the data with us but preferred that they not be acknowledged. Two deep seismic lines of profile across the Sylvania anticline and the Libby thrust belt were prepared by COCORP (The Consortium for Continental Reflection Profiling) in 1984–85 (Potter and others, 1986; Yoos and others, 1991). In 1986, graphs of the unmigrated data were generously made available for our use and are shown here (fig. 6). Locations of the profiles MT–1 (Montana–1) and MT–2 (Montana–2) are shown on plate 1 and in figure 2, and interpretation of the profiles (generously aided by my colleague, M.R. Reynolds) is shown in figure 6.

Most of the shallow reflectors (≤ 3 seconds) relate reasonably well to surface geology, even though the seismic data are not migrated and therefore are not precisely in the correct geographic position. The mafic sills in the lower part of the Prichard Formation (fig. 3) are known seismic reflectors and are visible on both of the seismic profiles. The Pinkham thrust fault, as identified on profile MT–2, projects from the surface to the logical position and dip angle shown, a position that agrees well with that obtained from other data from about 40 km farther to the south in the Libby thrust belt. Of less certain origin are the reflections recorded below the Wallace Formation and the Missoula Group on profile MT–2 near Pipe Creek. These may be reflections from sills in the Prichard Formation, or they may be unmigrated reflections from the steep faults and bedding in the area.

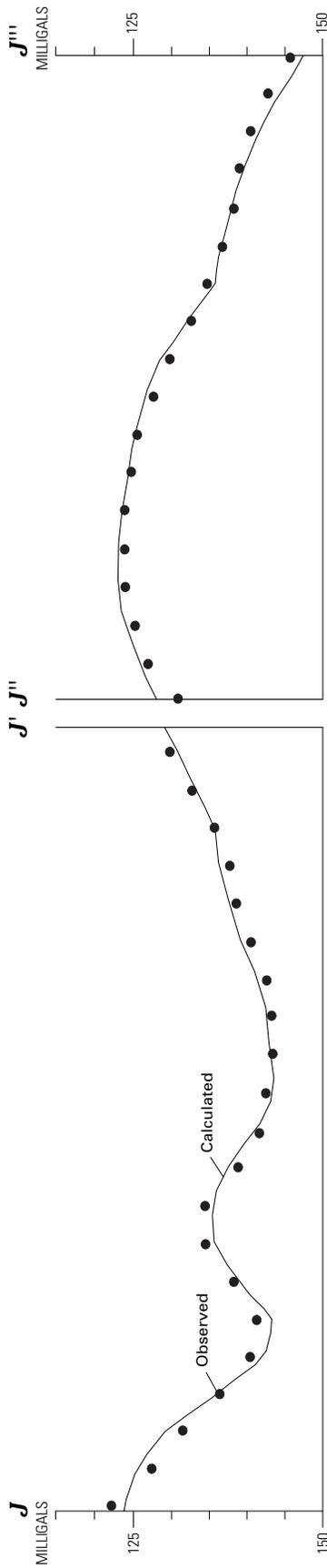
Below 3-seconds two-way travel time, the source of reflections is more speculative. The inferred basal surface of detachment is marked on profile MT–1 by a series of reflections and extends readily in profile MT–2 to separate various different domains of reflections. The depth to the basal surface varies from about 9 to 18 km across the area, and the surface dips about 15° in inferred crystalline basement rocks. These values do not differ drastically from the depth and dip of inferred basement rocks under the Purcell anticlinorium as shown for the Rocky Mountains of southern British Columbia in cross sections by Price and Fermor (1985) and

by Okulitch (1984, fig. 6). The strong reflections at and below 4 seconds (fig. 6) are, therefore, attributed to layered zones in the basement, perhaps mylonite, to the detachment zone for the older tectonic folding (?), or to strongly layered gneiss. No obvious reflection is present, at least along the profiles, for the Belt-basement contact. The lack of a basement reflection is most obvious on profile MT–1, where any reasonable thickness of the Prichard Formation requires that such a contact be at or above 4 seconds. Because the lowest part of the Prichard Formation in mid-Belt terrane is in the garnet zone of regional metamorphism and the Middle Proterozoic basement where drilled in western Montana is a mixture of granite, granitic gneiss, and some mafic intrusive rocks, a contact between metamorphosed Belt terrane and granite or granite gneiss would produce too little contrast to cause seismic reflections. A dissimilarity in basement rock types or structures is inferred from the contrast between the few deep seismic reflections above the Roderick Mountain thrust fault on profile MT–1 and the multiple prominent reflections below that thrust fault on profiles MT–1 and MT–2. None of the reflections are necessarily at the Belt-basement contact. A consequence of these observations is that the true thickness of the present Belt Supergroup, the thickest known sedimentary sequence of Middle Proterozoic rocks in the world, can only be determined by as yet undrilled deep boreholes.

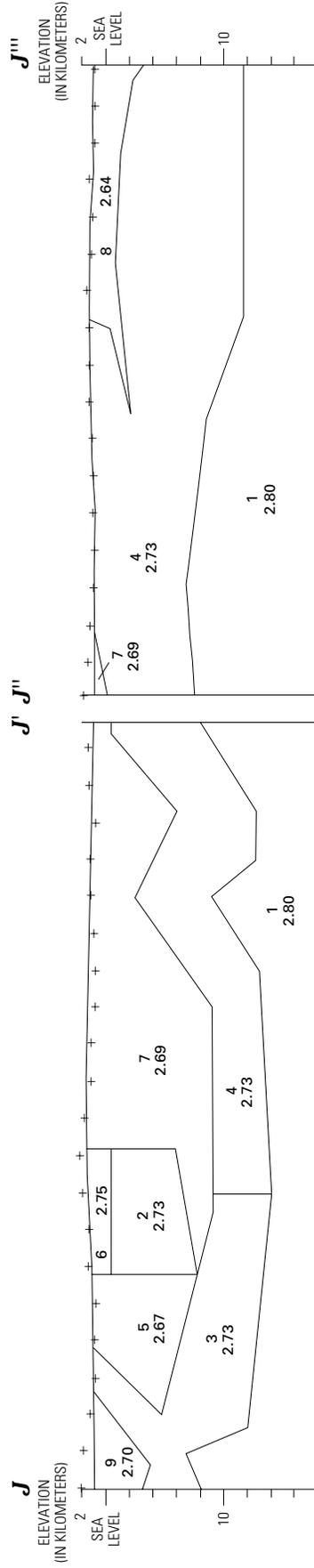
INTERPRETATION OF MAGNETOTELLURIC SOUNDINGS

By W.D. Stanley

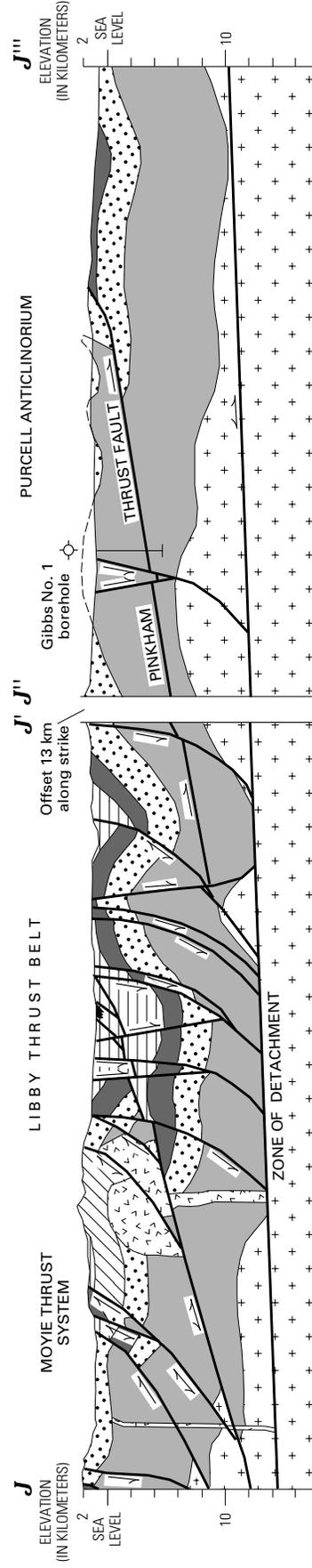
Extensive magnetotelluric surveys have been conducted across the Purcell anticlinorium and Libby thrust belt. Phoenix Geophysics supplied the data from a profile of five soundings (fig. 2) of a proprietary survey to me for inclusion in a study of regional structures. Another profile of the proprietary data, not shown in this report, is about 32 km south of the Phoenix profile and passes through the location of the Gibbs No. 1 borehole, a convenient geological calibration point. The magnetotelluric soundings from the survey are of high quality and quite unusual in that a striking low-resistivity zone was detected on all the soundings. Earlier audiomagnetotelluric studies (Wynn and others, 1977; Long, 1983, 1988) demonstrate that in the Prichard Formation a discontinuous zone, typically at depths of 0.9–2.5 km, is very conductive and has resistivities of a few ohm-meters or less. The vertical distribution of mineralized zones is indicated by the low resistivities in the resistivity log from the Gibbs No. 1 borehole (fig. 7). In the borehole, moderate amounts of sulfide minerals in members F, G, and H of the Prichard Formation cause resistivities of less than 200 ohm-m, and greater



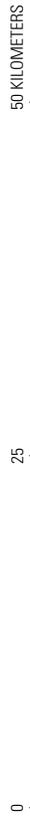
OBSERVED AND CALCULATED GRAVITY



GRAVITY MODEL



GEOLOGY



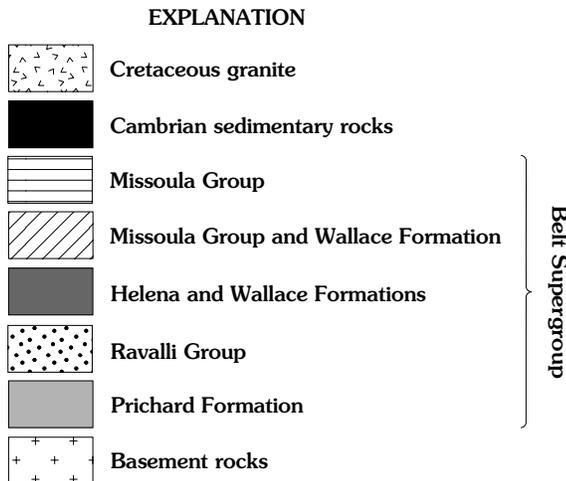


Figure 5 (above and facing page). Gravity block model of extended geologic cross section *J-J'* showing information about inferred lithology and structure beneath the Purcell anticlinorium, Libby thrust belt, northwestern Montana. Numbers on gravity model refer to body number and assumed density (in grams per cubic centimeter) as shown in table 1; for example, for body 1, the density is 2.80 g/cm³.

amounts of iron sulfide minerals at about 3 km (member E) and 5 km (members A–D?) produce resistivities of 2–20 ohm-m. The low resistivities are attributed to pyrite or pyrrhotite films and disseminated mineralized zones in the slightly carbonaceous argillitic unit. The low-resistivity zones in the Prichard Formation and other units of the Belt Supergroup represent easily mappable features for evaluation of mineralization in the Belt basin (Long, 1983).

Interpretations of the five soundings provided by Phoenix Geophysics were used to construct the resistivity cross section shown in figure 8. The soundings are one-dimensional in character (isotropic) in that the resistivities measured in the two coordinate directions of the field setup are very similar. The data were interpreted using interactive forward models of four and five layers, and the cross section was constructed by connecting the layered models from each sounding location (fig. 8). Accuracy of the interfaces obtained from the magnetotelluric data is not great, both because of the widely spaced sounding locations and because of the very large contrasts in resistivity between unmineralized and mineralized zones in the Belt Supergroup. Layer interfaces should be resolved, however, to within 10–15 percent of their true depth, particularly the top of the lowest resistivity layer that represents the deepest layer in the models shown in the cross section.

Most of the magnetotelluric data can be discussed in terms of two factors controlling resistivity in rocks of the Belt Supergroup—fluids and conductive mineralized rock. The 1,200–1,600-ohm-m layer beneath soundings 1 and 2

correlates with the Missoula Group, Helena and Wallace Formations, and Ravalli Group (fig. 8). These resistivities are typical for older carbonate and metasedimentary rocks that contain fresh pore waters, and they are characteristic of most Belt rocks above the Prichard Formation (Long, 1983). The 130–400-ohm-m units at the surface at soundings 3 and 4 are associated with the more mineralized conductive Prichard Formation, as are the conductive units (0.6–5 ohm-m) at soundings 1–4. The moderately low resistivity (250 ohm-m) in the Ravalli Group for the magnetotelluric model at sounding 5 is probably related to low-grade stratabound copper sulfide minerals, which are commonly present in the Spokane Formation, whereas the very low resistivities of 1.5 ohm-m for the model probably reflect the highly continuous iron sulfide zones in the Prichard Formation. The thicknesses of the low-resistivity units that form the basal layer on the magnetotelluric models could not be uniquely determined from the magnetotelluric soundings, even though the data extended to frequencies of 0.0005 Hz; however, estimates based on the magnetotelluric phase information suggest that conductive units must be thicker than 7.7 km (with an error of about 0.1 km). The intermediate layer of 20 ohm-m required at soundings 1 and 2 probably represents a part of the Prichard Formation that contains moderate amounts of iron sulfide minerals. The upper boundary of this low-resistivity layer approximately matches the interpreted location of the Pinkham thrust fault, which places highly resistive rocks of the Ravalli Group and Helena and Wallace Formations over the Prichard Formation (fig. 8). Magnetotelluric data should be effective in determining the lithology and depth to basement beneath Belt rocks, given a more extensive data set that would allow more accurate interpretations.

The magnetotelluric data have limitations in structural analysis because resistivities are controlled mostly by the percentages of metallic minerals and not by rock lithology. The magnetotelluric data require that conductive rocks, probably of the Prichard Formation, extend to depths of more than 10.8 km (with an error of about 1.6 km) below magnetotelluric soundings 1, 2, and 3 and that a low-resistivity (3–5 ohm-m) zone forms the bottom layer on the western part of the profile (fig. 8), corresponding approximately with the interpreted basal surface of detachment that separates crystalline basement units from the Prichard Formation.

The lithology of the basement in the study area cannot be resolved using the magnetotelluric data. Outcrops and boreholes in the region indicate basement of possible granitic gneiss, mafic intrusive rocks, and high-grade metasedimentary rocks. The Belt basin probably formed on stretched crust of Archean age that has a Middle Proterozoic (1,730 Ma) metamorphic overprint. This type of crust is not generally low in resistivity unless partial melting has occurred. Feldman (1976) pointed out that low resistivities can be produced in granitic rocks at depths of 10–15 km and temperatures of 500°C–600°C if 1–3 percent free water is

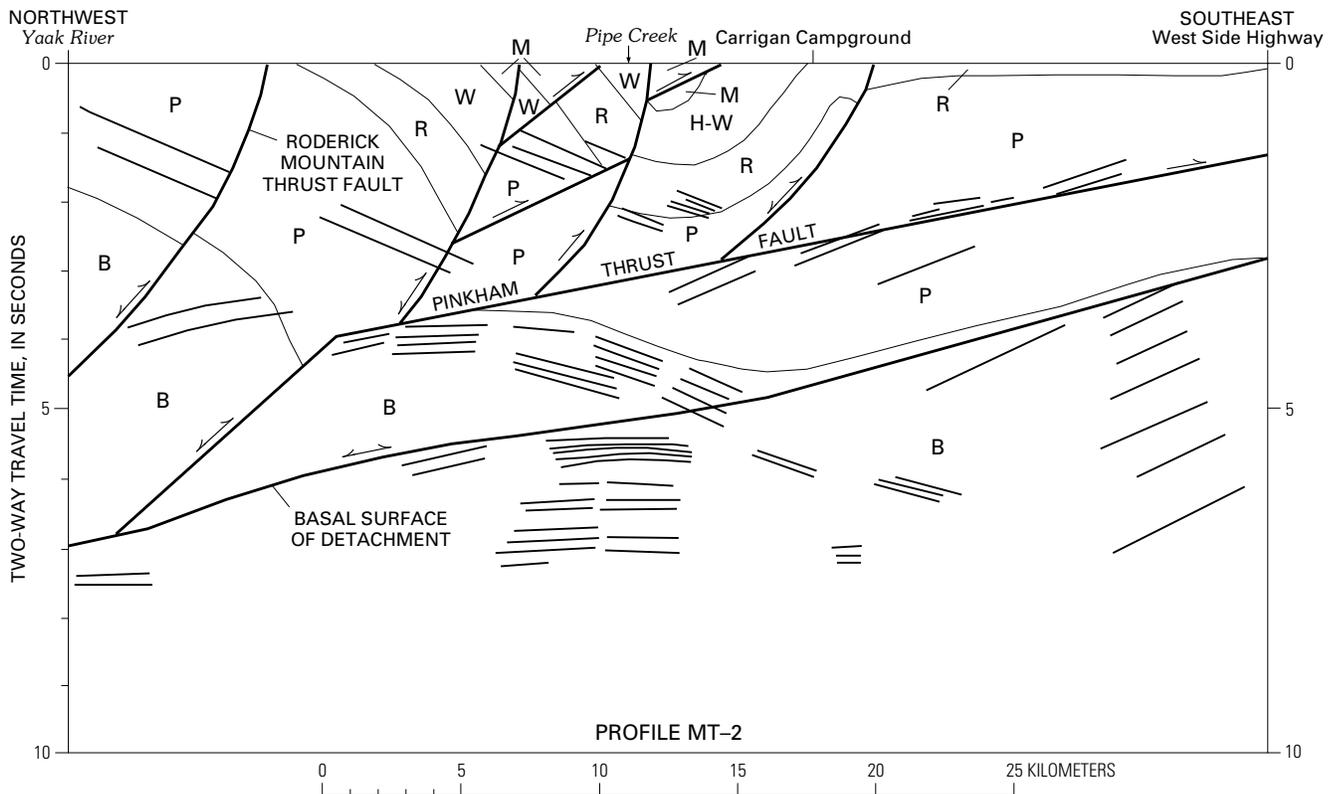
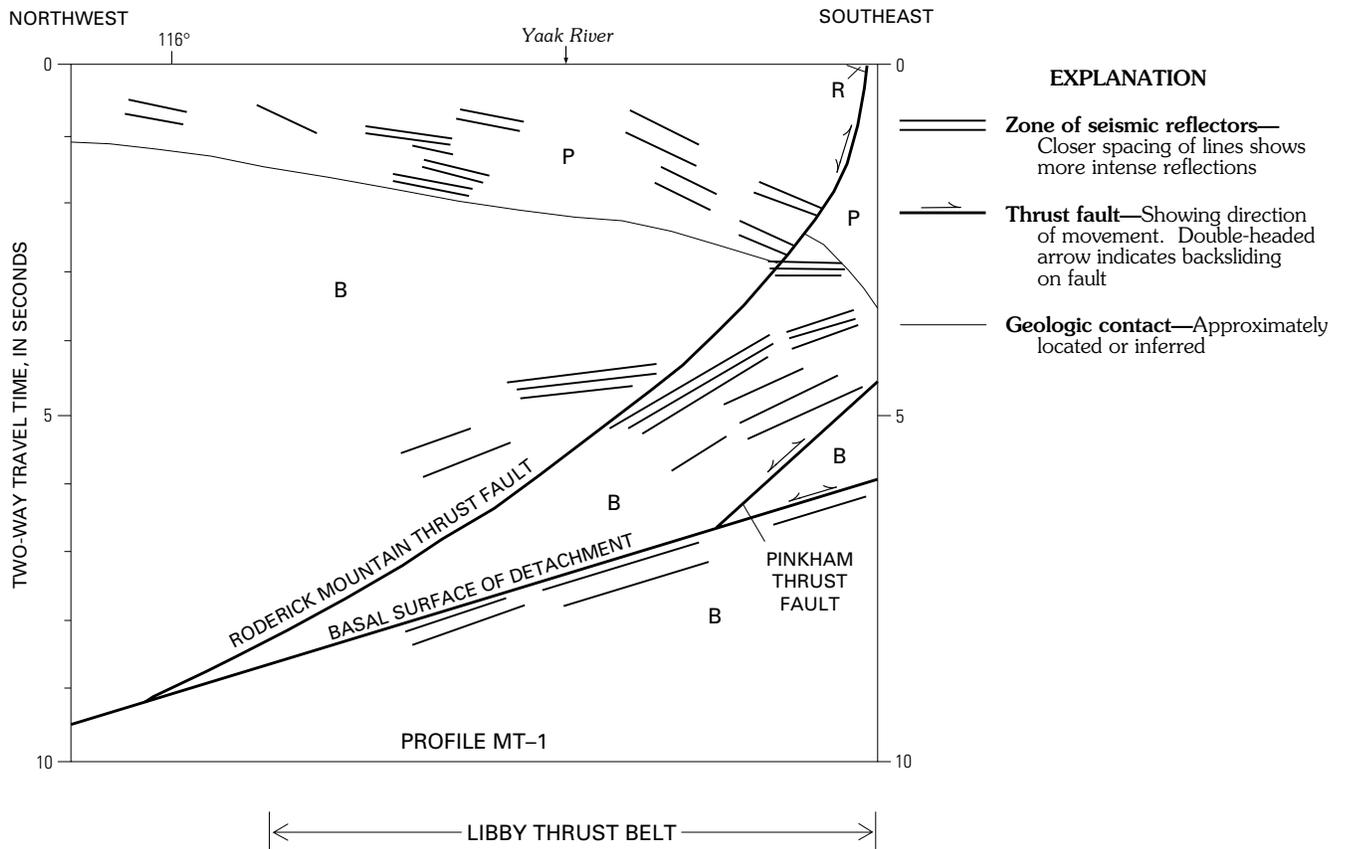


Figure 6. Interpretation of seismic reflection profiles MT-1 and MT-2, Libby thrust belt, northwestern Montana. Unmigrated data provided at H:V=1:1 at 6 km/sec. Surface geologic data are generalized from plate 1 of this report; 12 high-angle faults are not shown to avoid clutter. Geologic units: P, Prichard Formation; R, Ravalli Group; W, Wallace Formation; H-W, Helena and Wallace Formations; M, Missoula Group; S, Proterozoic mafic sills; B, crystalline basement rocks. Lines of profiles are shown in figure 2.

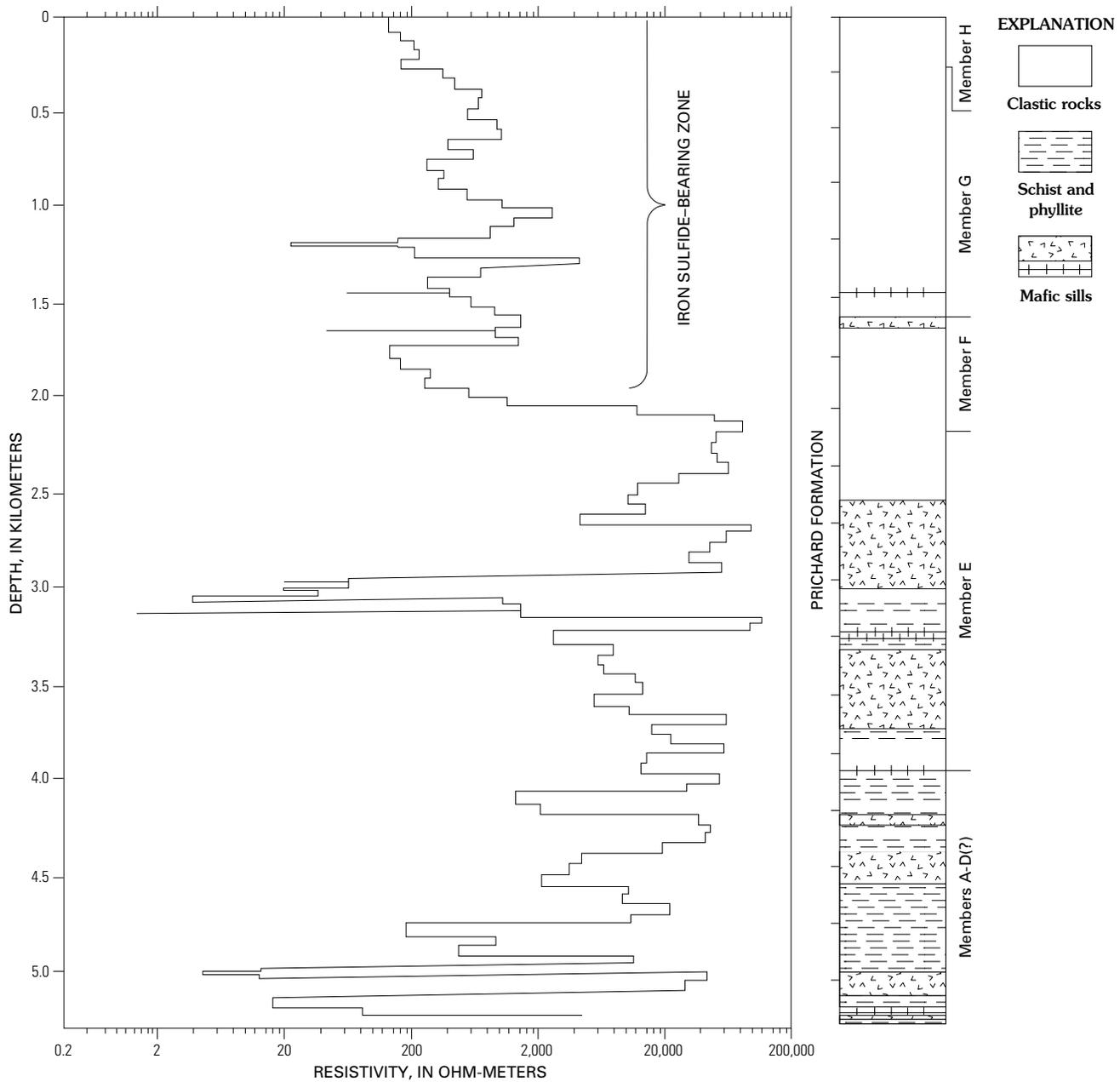


Figure 7. Generalized resistivity log (Dual Lateralog) of Gibbs No. 1 borehole, Flathead County, Montana. Electrical data courtesy of Atlantic Richfield and Marathon Oil Companies. Lithologic log simplified from figure 3.

present, perhaps from metamorphic processes. Continued extension of the crust beneath the Belt during sedimentation is indicated by periodic intrusion of mafic dikes and intrusions that have continental tholeiite affinities (Harrison and Cressman, 1993). Regional burial metamorphism reached the garnet grade of the greenschist facies (350°C or higher) in the lowest exposed Prichard during basin fill of at least 16 km of sediment and sills. Thus, there is no evidence in Belt rocks for temperatures of 500°C–600°C required to produce the type of conductors envisioned by Feldman (1976); however, a thermally related basement conductive zone could possibly now be present at depth beneath magnetotelluric

soundings 1, 2, and 3. Another possible line of thermal evidence is the absence of magnetic anomaly sources at depths of 10–15 km, presumed to be near the top of pre-Belt crystalline rocks. This absence of magnetic sources may relate to shallow Curie-point temperatures, above which magnetism does not exist (Mabey and others, 1978). Curie temperatures are about the same order of magnitude as those suggested by Feldman (1976), 500°C–600°C.

The extensive mafic volcanism and somewhat linear nature of the Belt-Purcell trend suggest that Belt rocks may have been deposited on pre-Belt rocks in a deep continental margin rift analogous to the Animike Basin of Minnesota

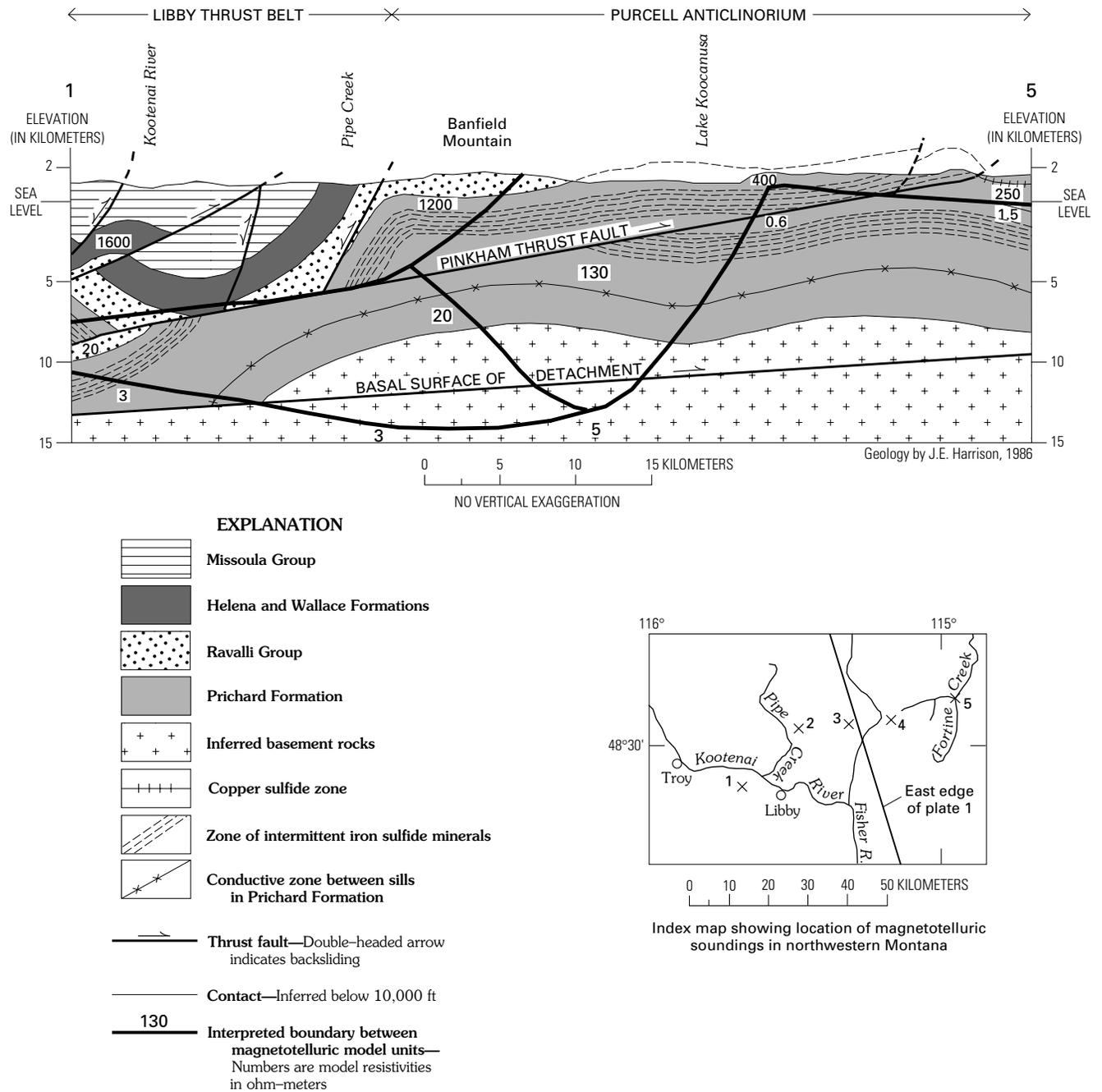


Figure 8. Magnetotelluric and geologic section across the eastern part of the Libby thrust belt and the western part of the Purcell anticlinorium. Numbers indicate magnetotelluric soundings, the locations of which are shown in figure 2.

and Wisconsin (Larue, 1981) or in a linear continental rift or aulocogen similar to the Amadeus Basin of Australia (Wells and others, 1970). Both the Amadeus and Animike basins contain large volumes of mafic volcanic rocks and thick Proterozoic anoxic shales that have high metal content (Lawler and Vadis, 1986; Wells and others, 1970). Dense high-velocity rocks that represent basement to the gravity and seismic methods may actually be dense, volcanogenic metasedimentary rocks that have high metallic mineral

concentrations, similar to rocks in the Animike and Amadeus basins. In addition, I speculate that the high conductivity of pre-Prichard crystalline basement in this area may be related to large amounts of metallic minerals. Thus, the magnetotelluric data can be used to postulate that units below the Belt Supergroup may be mineralized crystalline basement complex, unless temperatures are greater than 500°C–600°C.

SUMMARY AND CONCLUSIONS

Regional geophysical studies conducted by the U.S. Geological Survey in the northern Rocky Mountains during the past 25 years provide new insights about geologic framework and mineral resources. Conclusions presented in this report are based on integrating interpretations of these gravity, magnetic, seismic, and magnetotelluric data.

The gravity anomaly data show a marked correlation with major structures. The Purcell anticlinorium exhibits positive anomalies of more than 20 mGal, and the Sylvanite anticline exhibits positive anomalies of more than 10 mGal. Results of gravity modeling indicate that the Purcell anticlinorium and the Sylvanite anticline are very likely cored by stacks of thrust slices of dense crystalline basement rocks that account for the large gravity highs across these two structures.

The gravity anomaly data for the Cabinet Mountains Wilderness show a string of positive gravity anomalies about 6–8 mGal amplitude above background. The highs extend south-southeast in a belt from near the Kootenai River to as far as the latitude of Trout Creek. The gravity anomaly data and the distribution of magnetic anomalies suggest that the Cabinet Mountains Wilderness may be underlain by a large, uplifted granitic batholith. The gravity highs are interpreted to reflect intrusions along this feature, and the small positive magnetic anomalies are inferred to indicate near-surface sources that may be associated with small granitic intrusions or cupolas that are apophyses of the batholithic mass at depth, as shown in the gravity model.

The principal magnetic anomaly sources are igneous intrusive rocks, major fault zones, and magnetite-bearing sedimentary rocks of the Ravalli Group. Although the sources mainly are present in outcrop, in some cases they are partly or totally buried in the near-surface.

The most important magnetic anomalies in the principal study area are five distinct positive anomalies associated with Cretaceous or younger cupolas and stocks that are exposed or are known from drillholes to be present in the near-surface. These anomalies range in amplitude from 100 to more than 3,000 nT. Modeling of the magnetic anomaly data was not done because of the absence of long-wavelength magnetic anomalies having sources likely located in buried crystalline basement.

The lack of detectable anomalies is attributed to the relatively nonmagnetic character and deep burial of the basement rocks or to possible elevated Curie isotherms, which are compatible with one explanation of low resistivities obtained from magnetotelluric measurements. The mafic sills of dioritic to gabbroic composition show little or no magnetic response in outcrop, probably because of a reduction of magnetite content in the sills by chemical processes

related to interaction between hydrothermal fluids and cooling magmas of the intrusions.

Interpretation of seismic reflection data for the study area shows an inferred basal surface of detachment at depths of 9–18 km. Strong reflections at and below 4 seconds are attributed to stratification in the basement such as layered gneiss or mylonite along the detachment zone for the older tectonic folding. No obvious reflection is present, at least along the profiles, for the Belt-basement contact. Just below the Pinkham thrust fault, strong reflections attributed to stratification in crystalline basement rocks image relief in the basement on the western flank of the Purcell anticline.

Interpretation of magnetotelluric data shows a thick conductive basal layer that is incompatible with a crystalline basement composed of granitic gneiss, mafic intrusive rock, and high-grade metasedimentary rocks. This type of crust is not generally low in resistivity unless partial melting has occurred, perhaps at depths of 10–15 km and temperatures of 500°C–600°C if 1–3 percent free water is present. A possible explanation for a heat source at these depths is the lack of magnetic sources, which may indicate shallow Curie temperatures, as previously postulated. An alternative explanation is that pre-Prichard crystalline rocks are conductive simply because they contain large amounts of metallic minerals. This is certainly the case for the Prichard Formation because surface observations of variations in resistivity range from 0.6 to more than 400 ohm-m and most likely reflect the percentage of iron sulfide minerals and continuity of iron sulfide zones. Accuracy of the interfaces obtained from the magnetotelluric data is not great, both because of the widely spaced sounding locations and because of the very large contrasts in resistivity between unmineralized and mineralized zones in the Belt Supergroup.

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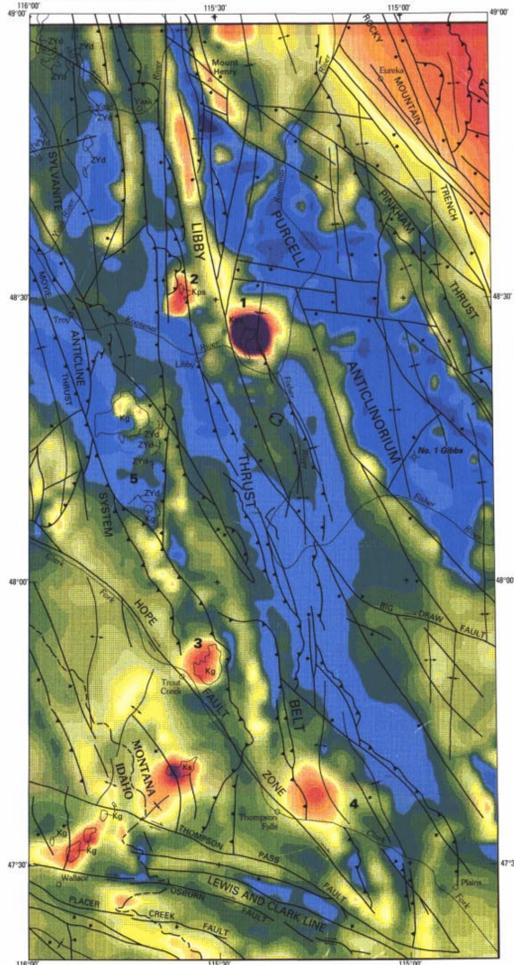
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EXPLANATION FOR MAPS A AND B

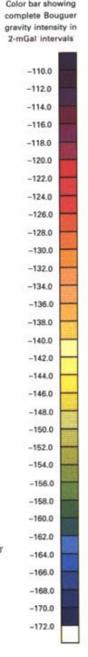
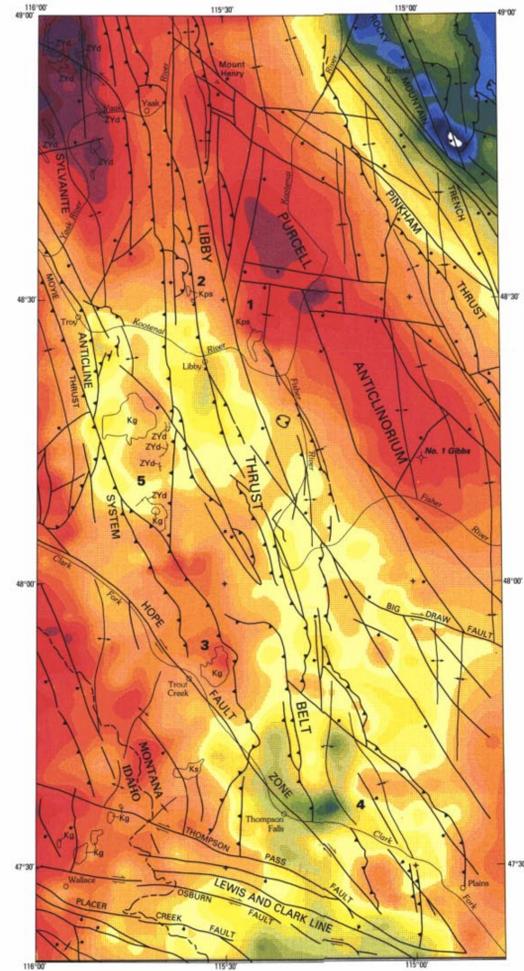
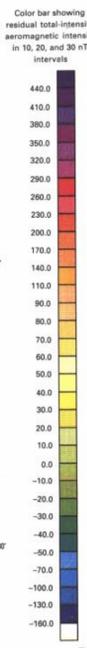
Kg Folak intrusive rocks (Cretaceous)
Ks Syenite (Cretaceous)
Kps Pyroxenite and spenite (Cretaceous)
Zyd Sill (Late and Middle Proterozoic)

Fault

Normal fault—Bar and ball on down-dropped side
Thrust fault—Sawtooth on upper plate
Tear fault—Arrows show direction of horizontal movement
Anticline—Showing crestline and dips of limbs
Syncline—Showing troughline and dips of limbs

4 Aeromagnetic anomaly referred to by number in text

Location of Atlantic Richfield-Marathon Oil No. 1 Gibbs borehole, NE 1/4 sec. 2, T. 28 N., R. 27 W., Flathead County, Montana

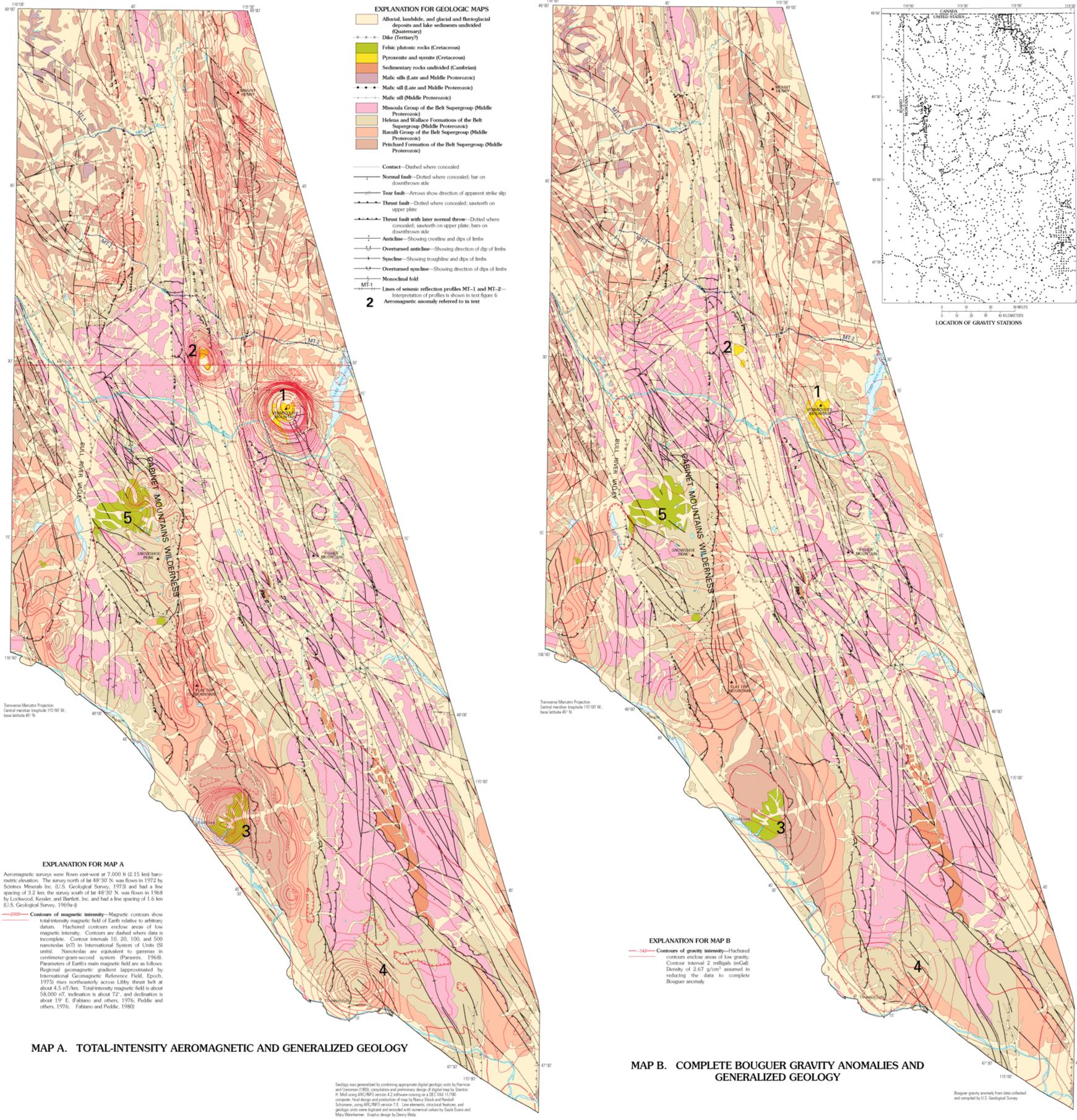


MAP A. RESIDUAL TOTAL-INTENSITY AEROMAGNETIC ANOMALIES AND STRUCTURAL FEATURES

MAP B. COMPLETE BOUGUER GRAVITY ANOMALIES AND STRUCTURAL FEATURES

MAPS SHOWING RESIDUAL TOTAL-INTENSITY AEROMAGNETIC ANOMALIES, COMPLETE BOUGUER GRAVITY ANOMALIES, GEOLOGY, AND STRUCTURAL FEATURES, LIBBY THRUST BELT, NORTHWESTERN MONTANA AND NORTHEASTERN IDAHO

By
M. Dean Kleinkopf
1997



MAPS SHOWING TOTAL-INTENSITY AEROMAGNETIC ANOMALIES, BOUGUER GRAVITY ANOMALIES, AND GENERALIZED GEOLOGY, LIBBY THRUST BELT, NORTHWESTERN MONTANA

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1997