Modeling of aeromagnetic data from the Precambrian Lake Owens mafic complex, Wyoming

PETER N. SHIVE
ROBERT S. HOUSTON } *Crustal Studies Program, Department of Geology and Geophysics, University of Wyoming, Laramie, Wyoming 82071*
RICHARD J. BLAKELY *U.S. Geological Survey, Menlo Park, California 94305*

ABSTRACT

Aeromagnetic anomalies overlying the Precambrian Lake Owens layered mafic complex and adjacent bodies in the Medicine Bow Mountains of southeast Wyoming help constrain their geometric and magnetic properties. Modeling of these anomalies shows that the magnetic part of the Lake Owens Complex corresponds well with its surface outcrop and is only about 1 km thick. The remanent magnetization is approximately as strong as the induced magnetization. The total magnetization of the complex is 5.8 × 10^{-3} emu/cc. Rocks this strongly magnetized, were they located in the deep crust, could account for long-wavelength magnetic anomalies. The anomaly also shows the presence of a small, strongly magnetic body to the northeast of the Lake Owens Complex. This is probably a small, separate mafic body or a piece of the complex broken and disrupted during tectonic activity and/or during later granite intrusion. The Mullin Creek layered mafic complex, to the west of the Lake Owens Complex, has weaker magnetization dominated by induced magnetization or a viscous remanent overprint in the direction of the present Earth's magnetic field. Its surface outcrop corresponds poorly with boundaries of magnetic units. A magnetic unit between the two mafic complexes may be a quartz diorite or a separate, shallow mafic body.

INTRODUCTION

The Lake Owens mafic complex is one of a series of mafic intrusions located in the Sierra Madre, Medicine Bow Mountains, and Laramie Mountains of southeastern Wyoming (Fig. 1). They are south of the Cheyenne belt, an apparent suture zone separating the Archean Wyoming province to the north from accreted island-arc terranes to the south (Hills and Houston, 1979; Karlstrom and Houston, 1984; Johnson and others, 1984). The mafic intrusions occur in a metavolcanic-metasedimentary succession and may represent the lower crustal zone of a continental-margin magmatic arc complex (Pallister and Aleinikoff, 1987).

The Lake Owens Complex is a relatively small cup-shaped intrusion with an exposed width of 9 km and exposed thickness of about 4.5 km (Houston and Ridgely, 1989). It consists of gabbro, norite, troctolite, and anorthosite in a sequence exhibiting rhythmic, cryptic, and size-graded layering, probably due to primary flow. Its magnetite content ranges between 0.2% and 8% by volume in thin sections (Ridgely, 1971). The Lake Owens Complex has largely escaped metamorphism and is the least altered of the mafic intrusions of southeastern Wyoming. The Mullin Creek mafic complex (Fig. 2) lies about 20 km to the west of the Lake Owens Complex. Although the two bodies are mineralogically and structurally similar, the Mullin Creek Complex is cut by numerous granitic intrusions, and the rocks are disrupted, altered, and locally metamorphosed (amphibolite grade).

Both bodies intrude a volcanogenic gneiss terrain (Fig. 2). The Lake Owens Complex is bordered on the south, east, and west by a quartz diorite intrusion, and to the north by a granite intrusion with a K-Ar age of 1.46 m.y. B.P. (Hills and Houston, 1979). The Mullin Creek Complex is bounded on the north and west by the Cheyenne belt, on the south and east by the gneiss. The age of the Mullin Creek Complex is constrained by the 1.778 ± 0.005 b.y. B.P. granite that cuts it (Premo, 1984) and by the fact that the oldest reliable age for nearby Proterozoic rocks south of the Cheyenne belt is 1.791 ± 0.012 b.y. B.P. (Premo, 1983). The Lake Owens

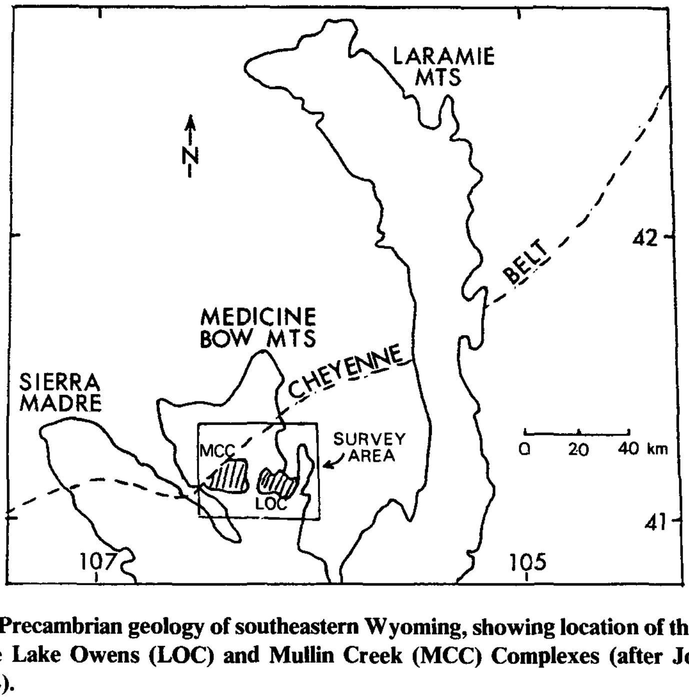

Figure 1. Precambrian geology of southeastern Wyoming, showing location of the Cheyenne belt and the Lake Owens (LOC) and Mullin Creek (MCC) Complexes (after Johnson and others, 1984).

Geological Society of America Bulletin, v. 102, p. 1317–1322, 7 figs., 1 table, September 1990.

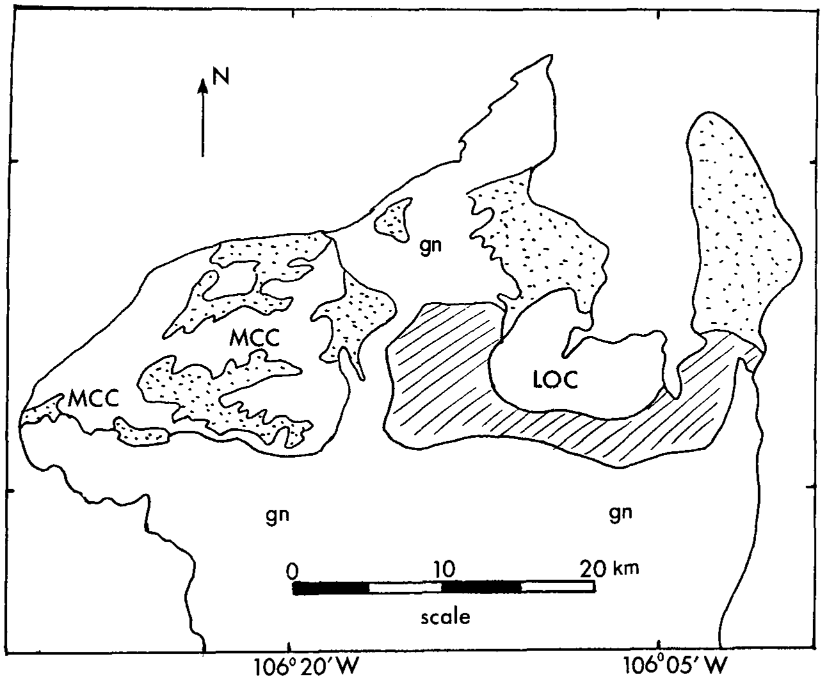

Figure 2. Geologic map of the area south of the Cheyenne belt in the Medicine Bow Mountains (after Houston and others, 1968). Granite bodies stippled; quartz diorite cross-hatched; gn, gneiss; MCC, Mullin Creek Complex; LOC, Lake Owens Complex.

Complex is presumably similar in age, as both were intruded during deformation and metamorphism (Pallister and Aleinikoff, 1987). Structural relations suggest that the complex was intruded by the 1.781 ± 0.006 b.y. B.P. (Premo, 1983) quartz diorite that borders it.

The Lake Owens Complex is the source of a significant magnetic anomaly, which appears on an aeromagnetic map of a part of the Medicine Bow Mountains (U.S. Geological Survey, 1976; Wood and Kaufmann, 1977). Flown in 1970 at a nominal barometric altitude of 3,660 m using an airborne fluxgate magnetometer, the survey was constructed from north-south flight lines spaced about 1.6 km apart. The resulting total-intensity map, reproduced at a scale of 1:62,500, has an estimated precision of ±25 gammas. The total-intensity anomaly over the Lake Owens body is about 3,600 gammas; anomalies of only 300–400 gammas overlie the Mullin Creek mafic complex to the west.

In this paper, we report on analysis and modeling of aeromagnetic anomalies over the Lake Owens Complex, the Mullin Creek Complex, and other magnetic units in the area. Our objective is to use the aeromagnetic data and other information to provide constraints on the structural and magnetic properties of these units. This information bears on problems of local and worldwide significance. Both of the mafic complexes are well exposed, but field mapping has been unable to provide reliable information about their thicknesses; thus, the method by which they were emplaced is still in doubt. The mineralogic similarity of the two complexes makes it difficult to understand why the anomaly above the Lake Owens Complex is ten times as intense as that over the Mullin Creek Complex. Finally, there has been much recent interest in the source of long-wavelength magnetic anomalies over continents (Williams and others, 1985/1986; Frost and Shive, 1986; Shive and others, 1989). Bodies with lower crustal affinity that are associated with strong magnetic anomalies are of great interest because they may qualify as potential sources for these long-wavelength anomalies.

MAGNETIC ANALYSIS

A part of the total-field aeromagnetic map, including the anomalies over the Lake Owens and Mullin Creek Complexes, was digitized at approximately 1.6-km intervals along flight lines. In order to better reproduce the rapid fluctuations of the Lake Owens anomaly, the digitization interval in that area was decreased to about 0.25 km. Subtraction of the 1970 IGRF field values converted the total-intensity measurements to anomaly values. These were then projected to a flat surface (Universal Transverse Mercator projection) and gridded at a 0.25-km spacing over an area about 46 km east-west by 37 km north-south (185 columns by 148 rows). Figure 3 shows the resulting total-field anomaly, contoured at a 100-gamma interval.

Cordell and Grauch (1985) introduced a technique for locating the edges of upper-crustal magnetic bodies. The method first requires transformation of the total-intensity anomaly into the pseudogravity anomaly (Baranov, 1957), which is the gravity anomaly that the

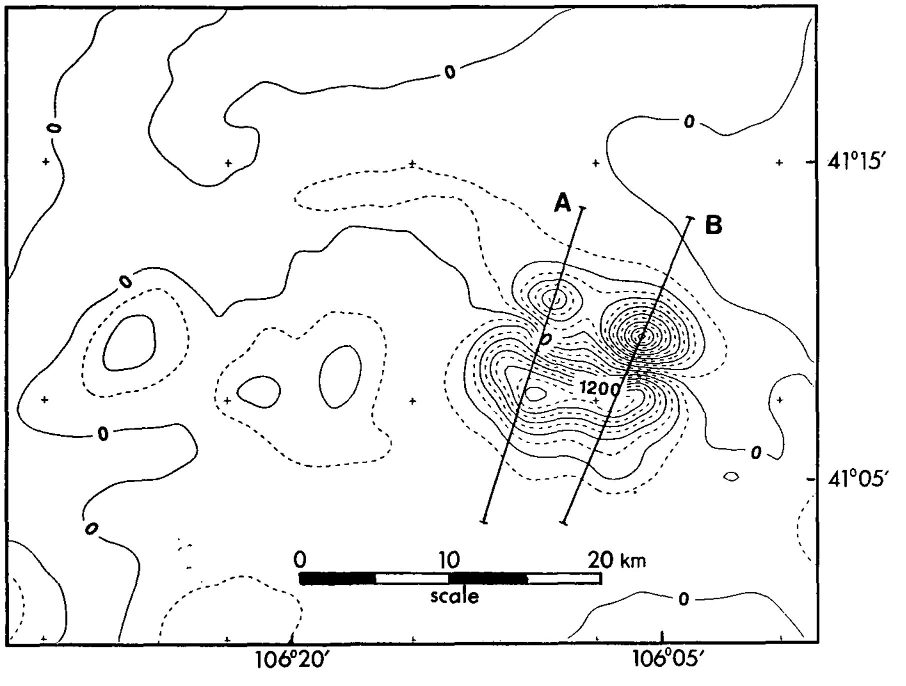

Figure 3. Total-field anomaly over the Lake Owens and Mullin Creek Complexes. A and B locate model cross sections of Figures 6 and 7.

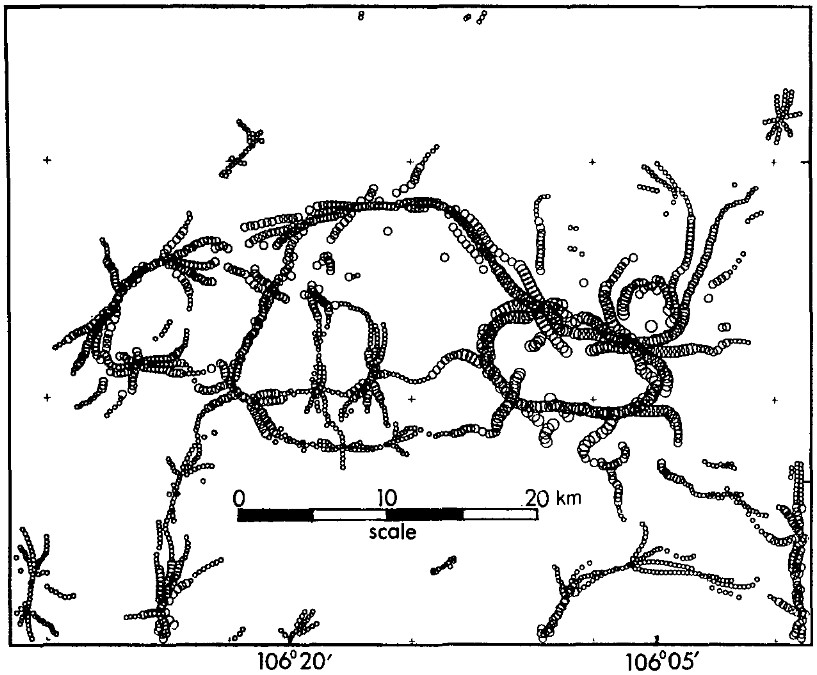

Figure 4. Locations of maxima in the horizontal gradient of the pseudogravity anomaly.

magnetized body would produce if it were of uniform magnetization and density. The next step is to calculate the magnitude of the horizontal gradient of the pseudogravity anomaly and to plot locations of their maxima, which approximately overlie the edges of the body. Blakely and Simpson (1986) extended the above procedure to speed and automate the final step, and their method was used to produce Figure 4. Figure 4 shows locations of horizontal gradient maxima in the pseudogravity anomaly; the size of the symbol is proportional to the value of the gradient at the maximum.

The pattern of maxima in the horizontal gradients shown in Figure 4 suggests that four important magnetic units are present in the central part of the survey area. We traced the major trends defined in Figure 4 to obtain the four polygons shown in Figure 5, which provide the outlines of magnetic units used in further modeling. Figure 5 also shows the outlines of the two complexes and of the quartz diorite unit. The main part of the Lake Owens anomaly is produced by the kidney-shaped polygon (no. 3) to the east. A smaller, more circular polygon (no. 4) is required to produce the strong magnetic anomaly minimum to the northeast of the body. The smaller Mullin Creek anomaly is produced by polygons 1 and 2. The tops of all polygons are 1,500 m below the survey level, which is approximate ground surface. The polygons are 1 km thick. This value was assigned after testing a series of models having different thickness. Thinner bodies approach the limit imposed by topographic relief in the area; a thicker Lake Owens polygon would have a total magnetization much less than the value measured by Shive and Morel (1980) from rocks from the complex.

After the body shape is known, the direction of magnetization giving the least error between the observed and calculated anomalies can be determined. We modified a single-body procedure (Blakely, 1981) to simultaneously compute the best-fitting magnetization parameters for several bodies for which the anomalies may overlap. Table 1 lists the results of this calculation. The root-mean-square error between the observed and calculated fields is only 21%, and inspection of the residual (observed minus calculated) anomaly shows that it is much higher in frequency than is the observed anomaly. On this basis, we feel that the four-polygon model gives a successful representation of the Lake Owens–Mullin Creek anomalies.

The remaining rms error results from the fact that magnetization in the polygons is not uniform, from departures of the magnetic units from the polygon geometry (vertical sides, flat tops and bottoms) and from the likely presence of smaller bodies that were not modeled. We could reduce this error by defining a more complex polygon model, but this would be tiresome because of the large number of degrees of freedom. Furthermore, our main interest is the large anomaly in the eastern part of the survey area. Accordingly, we chose to refine the vertical cross section of the Lake Owens Complex by modeling anomaly traverses.

We chose two southwest-northeast traverses that pass through the western and eastern anomaly high-low pairs, respectively (see Fig. 3). The eastern traverse (B) passes above polygon 4. Modeling was done using an interactive "2½"-dimen-

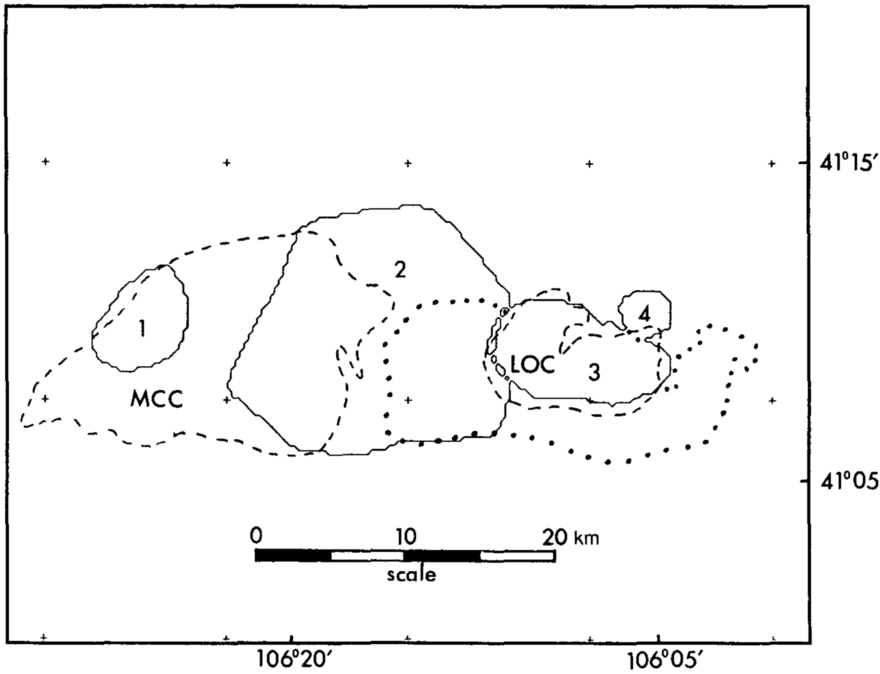

Figure 5. Polygon model (solid lines) derived from Figure 4. Dashed lines indicate the outlines of the Mullin Creek and Lake Owens Complexes. Dotted line indicates the outline of the quartz diorite.

TABLE 1. BEST-FITTING TOTAL MAGNETIZATION DIRECTIONS AND INTENSITIES FOR THE FOUR MODEL POLYGONS

Polygon	Declination (°)	Inclination (°)	Intensity (emu/cc)
1	01	65	1.61×10^{-3}
2	05	68	0.75×10^{-3}
3	21	24	5.83×10^{-3}
4	165	–53	5.14×10^{-3}

sional program (Saltus and Blakely, 1983) and using magnetization directions from Table 1. The program assumes that the body cross section is constant normal to the plane of the traverse, but the extent of the body (not necessarily infinite) may be specified in each of those directions. Figures 6 and 7 show the results of the modeling for traverses A and B, respectively. The model for traverse A is a simple cross section through polygon 3 at the traverse location, but the polygon model was altered to obtain best results for traverse B. First, polygon 3, although still 1,000 m thick, was placed 200 m deeper. Second, polygon 4 was made narrower, thicker, and deeper. These adjustments produced excellent agreement between calculated and observed values along the profile. For both traverses, successful models were obtained using simple tabular bodies with uniform magnetization.

DISCUSSION

Figure 5 allows a comparison of the magnetic units with geologic units (Fig. 2). For the Lake Owens body, the correspondence with polygon 3 is excellent, as the polygon outline follows the mapped contacts closely. Polygon 4, to the northeast of the main part of the complex, does not correspond to any mapped unit, but this is not surprising, as the traverse modeling (Fig. 7) indicates that it is not expected to crop out in the area.

Polygons 1 and 2 bear almost no relationship to the mapped outcrop of the Mullin Creek Complex. The western edge of polygon 1 traces part of the western contact of the complex with the Cheyenne belt, but the polygon defines a magnetic unit that includes only a small part of the western area of the complex. The west edge of polygon 2 falls over an extensively intruded part of the complex, but the rest of the polygon outline shows more of a relationship to the contact between the gneiss and the Cheyenne belt and Sherman granite to the north and the quartz diorite to the south. Alternate polygon interpretations of Figure 4 do not show any better correspondence with the Mullin Creek Complex.

There are two possible explanations for the mismatches. The Mullin Creek Complex may be nonuniformly magnetized, perhaps owing to internal intrusive activity, and may extend eastward beneath the gneiss and quartz diorite, possibly with a connection to the Lake Owens Complex. Alternately, although polygon 1 may correspond to a more magnetic part of the Mullin Creek Complex, polygon 2 may represent a part of the quartz diorite unit or a mafic body with no surface expression.

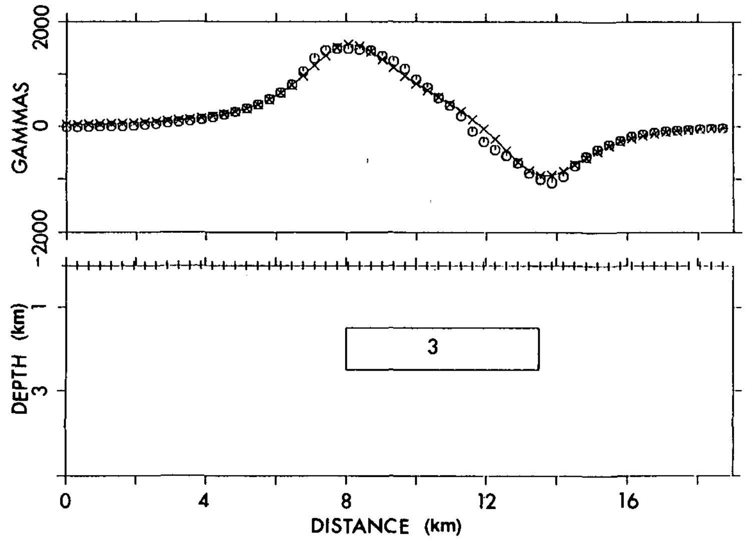

Figure 6. Southwest-northeast model cross section A across the Lake Owens Complex. O, observed magnetic anomaly values; X, anomaly values computed from the model. Profile location is shown in Figure 3.

The former explanation appears unlikely. The boundaries of polygons 1 and 2 do not reflect the pattern of intrusives within the Mullin Creek Complex. Furthermore, structural relations indicate that neither complex is likely to extend beneath the quartz diorite. If the quartz diorite represents the magmatic cap of either complex, it should lie to the northeast of the complex rather than south of the Lake Owens Complex.

We suggest that polygon 1 represents the western part of the Mullin Creek Complex, where it is relatively free of intrusives. Polygon 2 may be produced by the quartz diorite (dotted outline in Fig. 5). This interpretation is supported by two observations. First, the southwestern boundary of the quartz diorite follows polygon 2 closely. Second, the part of the quartz diorite between the complexes is notably less metamorphosed than is the eastern part, which could explain the difference in magnetic behavior there.

It is also possible that polygon 2 represents a third mafic body in this area. Johnson and others (1984) modeled a north-south gravity profile across the Medicine Bow Mountains. They proposed that the Lake Owens Complex occurs at the hinge of a complexly refolded nappe, with connection to a larger mafic body lying at depths of 2–5 km. If so, the Mullin Creek Complex and other shallow mafic bodies could be similarly related. The gravity anomaly (Johnson and others, 1984, p. 452) shows a continuous high across both mafic complexes, suggesting that mafic rocks may well occur beneath the quartz diorite and gneiss between the Mullin Creek and Lake Owens Complexes.

Polygon 4 may represent yet another such body. As noted above, the top of this body is below the top of the main part of the complex, which explains why it has not been discovered by surface mapping. It has the aspect of a vertical cylinder rather than a horizontal prism. Although control on its bottom is not as precise as on its top, best results were achieved when it was given a vertical extent of about 2 km. Its direction of magnetization (D = 165°; I = –53°) is almost antiparallel to the present field. The body must carry a remanence with steep (greater than 53°) negative (upward) inclination. Its Konigsburger ratio must be greater than 1 and is likely to be much greater. This in turn suggests that it cooled more rapidly than the main part of the Lake Owens Complex, which is consistent with its smaller size.

The strong magnetic intensity of this body suggests that it consists of mafic rocks. Although it is adjacent to the Lake Owens Complex, it is magnetized in a very different direction. Perhaps it is a completely separate small pluton. Alternately, it may be a piece of the Lake Owens

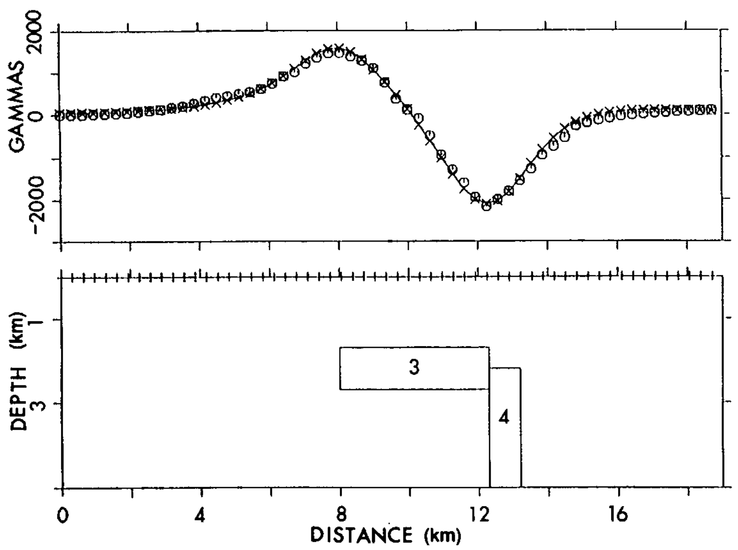

Figure 7. Southwest-northeast cross section B across the Lake Owens Complex. Symbols as in Figure 6.

Complex that was disrupted and possibly remagnetized during initial emplacement, during intrusion of the Sherman granite, or during Laramide tectonic activity.

The magnetic analysis shows that the Lake Owens and Mullin Creek Complexes are quite different magnetically. It is clear from Table 1 that the Mullin Creek Complex anomaly (polygon 1) is dominated by induced or viscous remanent magnetization. For the Lake Owens Complex anomaly (polygon 3), the magnetization has a significant remanent component.

This conclusion is in accord with magnetic studies of samples from both areas. A paleomagnetic study of the Mullin Creek Complex (C. M. Keefer and P. N. Shive, unpub. data) was abandoned when remanent magnetization proved to be weak and unstable, and significant viscous magnetization was acquired in the laboratory in a few days. Shive and Morel (1980) carried out a successful paleomagnetic study on the exposed part of the Lake Owens Complex. They found stable remanence at almost all of 30 sites throughout the body, with NRM (natural remanent magnetization) parameters of D = 28.5°, I = –24.9°, α_{95} = 24.2°. Susceptibility values for the same samples had a geometric mean of 1.6×10^{-3} cgs, and the Konigsburger ratios (Q, computed in an inducing field of 0.65 oe) for these samples had an average of about 50.

The total magnetization of a body is the vector sum of induced magnetization plus NRM. If we use the total magnetization for polygon 3 from Table 1, the NRM direction from the Shive and Morel (1980) study, and the induced direction from the present-field orientation (D = 14.5°, I = 65°), we can compute the ratio of induced magnetization to NRM. This computation yields a value for Q of 0.84. This value is probably a better representation of the Konigsburger ratio for the body as a whole than is the one determined from the paleomagnetic study at surface exposures, because the paleomagnetic sites were deliberately chosen to sample finer-grained rocks and to avoid concentrations of magnetite. In any case, values of Q less than 1 are more typical for coarse-grained intrusive rocks (Nagata, 1961), and the high value obtained from the Shive and Morel (1980) study indicates that their sites were more effectively located for a paleomagnetic analysis.

The total magnetization intensity for polygon 3 is 5.83×10^{-3} emu/cc (see Table 1), which is only about one-third the average NRM intensity from the Shive and Morel (1980) study. Perhaps Shive and Morel sampled from sites where NRM intensities were unusually high. If so, those same sites had unusually low susceptibilities, in order to give an average Konigsburger ratio of 50. The discrepancy could be corrected by thinning polygon 3 from 1 km to about 300 m. This seems unlikely, as the complex has about 200 m of relief with no significant vertical variation. Also, the structure dips steeply to the northeast, and it is difficult to imagine how such a thin slice could have been sheared off and still retain structural integrity. It also seems unlikely to us that the Lake Owens Complex is much thicker than 1 km. Although a thicker body could satisfy the magnetic anomaly over the complex, it would require that the magnetization be correspondingly less intense. Increasing the thickness to 3 km would require a magnetization almost an order of magnitude smaller than the observed NRM values.

SUMMARY AND INTERPRETATION

The two layered complexes of the southern Medicine Bow Mountains and a related gabbroic intrusion, the Elkhorn Mountain intrusion of the western Park Range of Colorado (Snyder, 1980), are the three largest gabbroic bodies of the central and southern Rocky Mountains. All are located within 20 km of the Cheyenne belt that separates the Archean Wyoming province from the Proterozoic of southern Wyoming, Colorado, Arizona, and New Mexico.

The general consensus of Precambrian geologists and geochemists in recent years is to consider the Cheyenne belt as the first of a series of sutures where island arcs and other exotic Proterozoic terranes were attached to the Archean continent to develop the Proterozoic crust of this area (Hills and Houston, 1979; Condie, 1982; Karlstrom and Houston, 1984; Reed and others, 1987; Bennett and DePaolo, 1987).

Hills and Houston (1979) and Karlstrom and Houston (1984) developed a plate-tectonic model for the Medicine Bow Mountains that involved collision of a Proterozoic island arc with Early Proterozoic Archean province continental margin along a south-dipping subduction plate. Ramping of the island arc over the continental margin promoted low-angle thrusting of both the Early Proterozoic continental-margin succession and the arc volcanics. As the arc massif approached and collided with the margin, thrusts and beds were rotated to nearly vertical attitude. More detailed study of the Cheyenne belt by Duebendorfer and Houston (1987) has refined the plate-tectonic model and has demonstrated that the Cheyenne belt proper is composed of blocks that expose deeper levels of the crust from north to south.

The magnetic and gravity data offer support for these geologic concepts. Gravity and magnetic data suggest that a large mafic body underlies the two mafic complexes and quartz diorite of the Medicine Bow Mountains and that the underlying mafic body extends some distance south of the present exposures of the Lake Owens and Mullen Creek mafic complexes.

Both the Lake Owens and Mullen Creek mafic complexes are leucocratic and do not have a major component of ultramafic rocks. The Lake Owens Complex, for example, has olivine gabbro at its base and has petrologic and stratigraphic characteristics like the upper part of a more typical layered complex such as the Bushveldt or Stillwater (Houston and Orback, 1976). The Mullen Creek Complex is so disrupted and intruded by granite that its stratigraphy is not well understood.

Magnetic data show that the Lake Owens mafic complex is approximately 1 km thick, compared with its stratigraphic thickness which is greater than 5 km. Layering in the Lake Owens Complex dips 60°–70° northeast, suggesting that the complex has been tilted. The Lake Owens Complex is thought to have developed from successive magma injections (Myers and others, 1987), with the later injections of increasing volume. The magnetic and gravity data support a model in which the Lake Owens and Mullen Creek Complexes were part of a larger layered complex that intruded the volcanic pile. The complexes were detached and thrust to the north,[1] were subsequently invaded by quartz diorite, deformed, and metamorphosed, and were invaded by granite.

The magnetic analysis of the Lake Owens Complex also has important implications for crustal magnetization. It has been observed by many authors (see compilation in Mayhew and others, 1985) that long-wavelength magnetic anomalies require sources in the deep crust with total magnetization of about 5×10^{-3} emu/cc. This is inconsistent with studies of rocks from lower-crustal cross sections now exposed at the surface (Wasilewski and Fountain, 1982; Schlinger, 1985; Williams and others, 1985/1986; Shive and Fountain, 1988), which show magnetization averaging less than 1×10^{-3} emu/cc. The search for the missing magnetization in the deep crust is one of the most important problems in crustal magnetization.

Mafic intrusions like the Duke Island Complex (Irvine, 1974) and the Lake Owens Complex are among the candidate bodies capable of providing the missing magnetization (Frost and others, 1989). These layered plutons in many cases contain gabbroic units with as much as 15% magnetite by volume. They are relatively primitive plutons with calc-alkalic affinities that may provide the main source of magnetic anomalies over dead magmatic arcs.

The vector decomposition in the preceding section indicates that the induced magnetization of the Lake Owens Complex is 4.51×10^{-3} emu/cc. This shows that as a whole, the body has higher susceptibility and lower NRM than do the samples from the Shive and Morel (1980) study. Remanent magnetization does not appear to be an important source of magnetic anomalies for deep-seated crustal bodies (Shive, 1989). Even so, the Lake Owens Complex contains rocks that, were they present in sufficient quantity in the deep crust, are capable of providing sources for long-wavelength magnetic anomalies through induced magnetization alone.

ACKNOWLEDGMENTS

The National Science Foundation (NSF AP88-03430) provided partial financial support for this study.

REFERENCES CITED

Baranov, V., 1957, A new method for interpretation of aeromagnetic maps: Pseudo-gravimetric anomalies: Geophysics, v. 22, p. 359–383.

Bennett, V. C., and DePaolo, D. J., 1987, Proterozoic crustal history of the western United States as determined by neodymium isotopic mapping: Geological Society of America Bulletin, v. 99, p. 674–685.

Blakely, R. J., 1981, A program for rapidly computing the magnetic anomaly over digital topography: U.S. Geological Survey Open-File Report 81-298, 46 p.

Blakely, R. J., and Simpson, R. W., 1986, Approximating edges of source bodies from magnetic or gravity anomalies: Geophysics, v. 51, p. 1494–1498.

Condie, K. C., 1982, Plate-tectonics model for Proterozoic continental accretion in the southwestern United States: Geology, v. 10, p. 37–42.

Cordell, L., and Grauch, V.J.S., 1985, Mapping basement magnetization zones from aeromagnetic data in the San Juan basin, New Mexico, *in* Hinze, W. J., ed., The utility of regional gravity and magnetic anomaly maps: Tulsa, Oklahoma, Society of Exploration Geophysicists, p. 131–147.

Duebendorfer, E. M., and Houston, R. S., 1987, Proterozoic accretionary tectonics at the southern margin of the Archean Wyoming craton: Geological Society of America Bulletin, v. 98, p. 554–568.

Frost, B. R., and Shive, P. N., 1986, Magnetic mineralogy of the lower continental crust: Journal of Geophysical Research, v. 91, p. 6513–6522.

Frost, B. R., Shive, P. N., and Blakely, R. J., 1989, Is the source for long wavelength magnetic anomalies really "missing"? [abs.]: Eos (American Geophysical Union Transactions), v. 70, p. 315.

Hills, F. A., and Houston, R. S., 1979, Early Proterozoic tectonics of the central Rocky Mountains, North America: Contributions to Geology, v. 17, p. 89–109.

Houston, R. S., and Orback, C. J., 1976, Geologic map of the Lake Owens quadrangle, Albany County, Wyoming: U.S. Geological Survey Map GQ-1034, scale 1:24,000.

Houston, R. S., and others, 1968, A regional study of rocks of Precambrian age in that part of the Medicine Bow Mountains lying in southeastern Wyoming, with a chapter on the relationship between Precambrian and Laramide structure: Laramie, Wyoming, Geological Survey of Wyoming Memoir, v. 1, 167 p.

Irvine, T. N., 1974, Petrology of the Duke Island ultramafic complex, southeastern Alaska: Geological Society of America Memoir 138, 240 p.

Johnson, R. A., Karlstrom, K. E., Smithson, S. B., and Houston, R. S., 1984, Gravity profiles across the Cheyenne belt, a Precambrian crustal suture in southeastern Wyoming: Journal of Geodynamics, v. 1, p. 445–472.

Karlstrom, K. E., and Houston, R. S., 1984, The Cheyenne belt: Analysis of a Proterozoic suture in southern Wyoming: Precambrian Research, v. 25, p. 415–446.

Mayhew, M. A., Johnson, B. D., and Wasilewski, P. J., 1985, A review of problems and progress in studies of satellite magnetic anomalies: Journal of Geophysical Research, v. 90, p. 2511–2522.

Myers, J. D., Patchen, A. D., and Houston, R. S., 1987, The Lake Owens mafic complex, southeast Wyoming: 1. Geologic field relations [abs.]: Eos (American Geophysical Union Transactions), v. 68, p. 438.

Nagata, T., 1961, Rock magnetism: Tokyo, Japan, Maruzin, 350 p.

Pallister, J. S., and Aleinikoff, J. N., 1987, Gabbroic plutons south of the Cheyenne belt: Underpinnings of an Early Proterozoic continental-margin arc: Geological Society of America Abstracts with Programs, v. 19, p. 325.

Premo, W. R., 1983, Uranium-lead-zircon geochronology of some Precambrian rocks from the Sierra Madre Range, Wyoming [M.S. thesis]: Lawrence, Kansas, University of Kansas, 106 p.

——1984, U-Pb zircon geochrons of Early Proterozoic plutonism in N Colorado and SE Wyoming: Geological Society of America Abstracts with Programs, v. 16, p. 251.

Reed, J. C., Jr., Bickford, M. E., Premo, W. R., Aleinikoff, J. N., and Pallister, J. S., 1987, Evolution of the Early Proterozoic Colorado province—Constraints from U-Pb geochronology: Geology, v. 15, p. 861–865.

Ridgely, J., 1971, The Lake Owens Complex, Wyoming [M.S. thesis]: Laramie, Wyoming, University of Wyoming, 114 p.

Saltus, R. W., and Blakely, R. J., 1983, Hypermag—An interactive two-dimensional gravity and magnetic modeling program: U.S. Geological Survey Open-File Report 83-241, 28 p.

Schlinger, C. M., 1985, Magnetization of the lower crust and interpretation of regional magnetic anomalies: Example from Lofoten and Vesteralen, Norway: Journal of Geophysical Research, v. 90, p. 11484–11504.

Shive, P. N., 1989, Can remanent magnetization in the deep crust contribute to long wavelength magnetic anomalies?: Geophysical Research Letters, v. 16, p. 89–92.

Shive, P. N., and Fountain, D. M., 1988, Magnetic mineralogy in an Archean crustal cross section: Implications for crustal magnetization: Journal of Geophysical Research, v. 93, p. 12177–12186.

Shive, P. N., and Morel, J. A., 1980, Paleomagnetism of the Precambrian Lake Owens Complex, Medicine Bow Mountains, Wyoming: Contributions to Geology, v. 19, p. 1–8.

Shive, P. N., Blakely, R. J., and Frost, B. R., 1990, Magnetic properties of the lower continental crust, *in* Fountain, D. M., Arculus, R., and Kay, R. M., eds., Continental lower crust: Washington, D.C., American Geophysical Union (in press).

Snyder, G. L., 1980, Geologic map of the northernmost Park Range and southernmost Sierra Madre, Jackson and Routt Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1113, scale 1:48,000.

*U.S. Geological Survey, 1976, Aeromagnetic map of Medicine Bow, Wyo*ming: U.S. Geological Survey Open-File Report 76-687, scale 1:62,500.

Wasilewski, P., and Fountain, D. M., 1982, The Ivrea zone as a model for the distribution of magnetization in the continental crust: Geophysical Research Letters, v. 9, p. 333–336.

Williams, M. C., Shive, P. N., Fountain, D. M., and Frost, B. R., 1985/1986, Magnetic properties of exposed deep crustal rocks from the Superior province of Manitoba: Earth and Planetary Science Letters, v. 76, p. 176–184.

Wood, J. D., and Kauffman, H. E., 1977, Comparison of ground magnetic values of vertical, horizontal and total field intensity with airborne total field measurements in the Medicine Bow, Wyoming, area: U.S. Geological Survey Open-File Report 77-827, 11 p.

Manuscript Received by the Society May 19, 1989
Revised Manuscript Received November 7, 1989
Manuscript Accepted January 1, 1990

---

[1] Recent mapping at the northern margin of the Lake Owens Complex by R. S. Houston (unpub. data) shows that the exposed top of the complex is a fault that dips southwest at a low angle.

Printed in U.S.A.