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Gravity Interpretation of the Laramie Anorthosite Complex, Wyoming

ABSTRACT

Interpretation of a gravity study of the Laramie anorthosite complex limits petrogenetic models. Bouguer gravity anomalies within the anorthosite average about −155 mgal, decrease by 12 mgal over younger granite, and increase up to 20 mgal over bordering syenite bodies. The gravity field over the anorthosite is low with respect to the metamorphic rocks on the northern border. Computed models indicate that the anorthosite mass is a plate 4 km thick with no apparent feeder pipes and is not underlain by a high-density mass. High gravity gradients and ubiquitous surface association of gravity highs over norite-syenite suggest that norite floors these syenite bodies at a depth as shallow as 0.5 km. Computed thickness of norite is about 4 km. From the gravity data, the norite-syenite seems to rim the anorthosite, except where younger intrusions may have disturbed this relation. Minimum calculated mass for respective rock types are: anorthosite, 9.7×10^{18} g; norite, 2.3×10^{18} g; syenites, 6.0×10^{17} g. The parent magma is estimated to have been of noritic anorthosite composition. Petrogenetic models derived from these data suggest that (1) in situ differentiation of gabbroic magma is unlikely, and (2) anorthosite initially differentiated from the parent magma followed by norite and syenites, then this sequence rose into the present domal configuration as a partly consolidated mush.

INTRODUCTION

Although the origin of layered mafic complexes that contain anorthosite, such as the Bushfeld, Stillwater, and Skaergaard complexes, is relatively well known, the petrogenesis of massif-type anorthosite complexes is poorly understood. Critical to the interpretation of any anorthosite complex is the amount of anorthosite present and the amount of more mafic rock such as gabbro associated with the anorthosite complex at the surface or at depth. Layered mafic complexes are floored by gabbroic rocks such as in the Stillwater complex (Hess, 1960; Bonini, 1969), but anorthosite massifs do not seem to be underlain by rocks of greater density (Simmons, 1964). Quantitative interpretation of parent magma and genesis of these complexes depends on the masses of the different rocks involved. These types of data can only be obtained by geophysical methods; gravity interpretation is a highly suitable geophysical technique. In order to determine petrogenesis, this study is based on a gravity interpretation of the Laramie anorthosite complex located in the Laramie Mountains, Wyoming.

GEOLOGY

The southern portion of the Laramie Mountains is a broad asymmetrical anticline with Precambrian rocks exposed in the core (Fig. 1). Flanking the range to the east and west are sedimentary basins containing up to 5 km of sedimentary rocks.

Klugman (1966) defined the relative ages of the various rock types to be in order of decreasing age: gneisses and schists, anorthosite, gabbroic (noritic) anorthosite, olivine gabbroic anorthosite, norite, hypersthene syenite, hornblende syenite, Sherman Granite, and quartzofeldspathic dikes. Hills (1972, oral commun.) found Rb-Sr dates of approximately 2.5 b.y. for granitic gneisses north of the Laramie anorthosite. The youngest crystalline rock in the region, the Sherman Granite, has Rb-Sr dates of 1.33 to 1.38 b.y. (Giletti and Gast, 1961; Hills and others, 1968; Peterman and others, 1968). Samples of biotite and hornblende from within the anorthosite gave K-Ar

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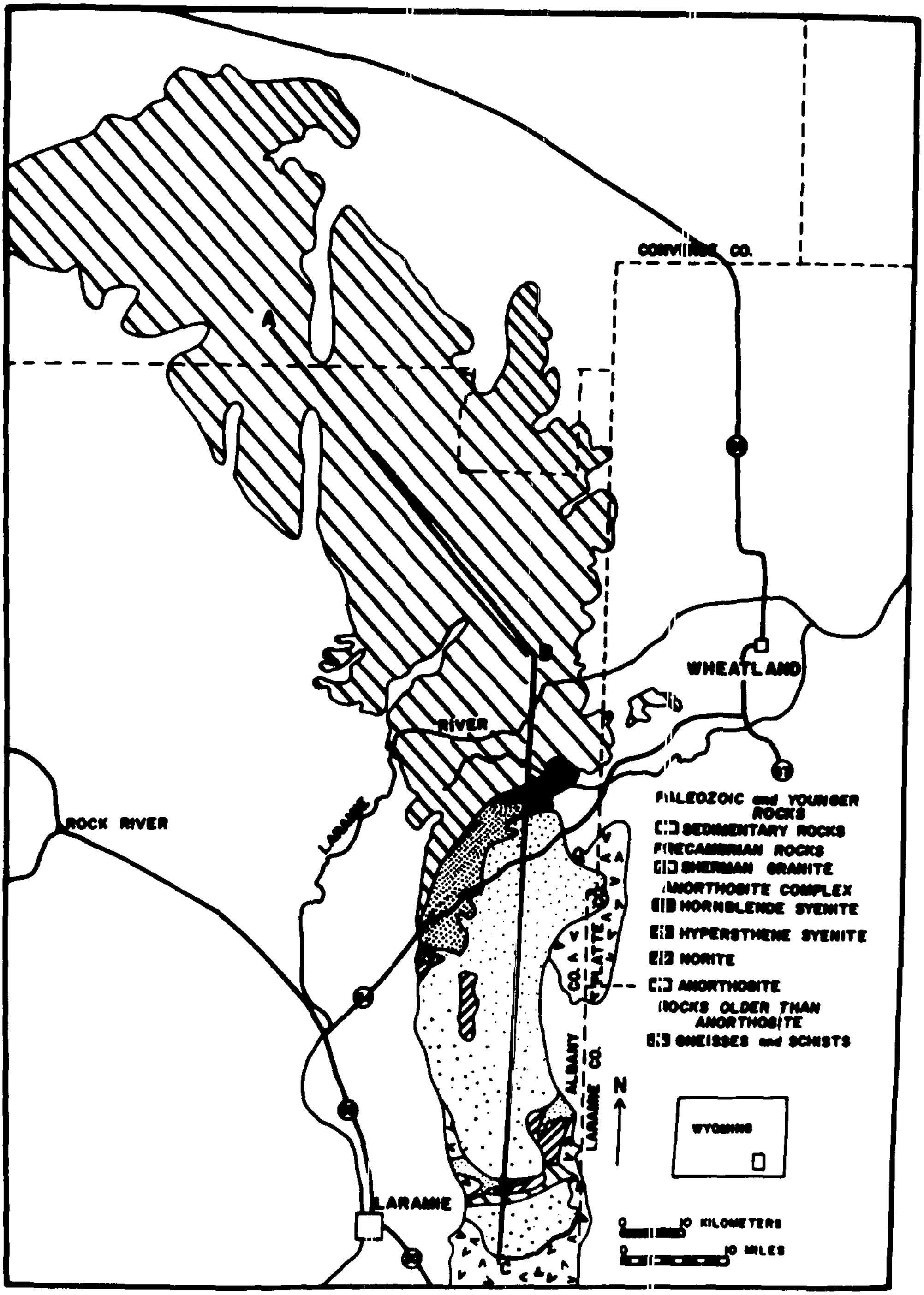

Figure 1. Index map of Laramie anorthosite complex. Profile A-B-C is location of gravity interpretation in Figure 8.

dates of 1.40 and 1.53 b.y., respectively (Hills, 1972, oral commun.).

The older metamorphic rocks consist predominantly of amphibolite, biotite gneiss, quartzofeldspathic gneiss, and minor amounts of metasedimentary marbles and quartzites. These rocks are of middle to upper amphibolite facies grade and border the northern part of the massive Laramie anorthosite complex (Fields, 1963; Hodge, 1966b; Smith, 1967). In the south-central part of the complex, an east-west strip of igneous and metamorphic rocks bridges the anorthosite and divides it into two masses, a larger northern mass and a southern mass (Newhouse and Hagner, 1957). The eastern and southern margins of the anorthosite complex have been intruded by Sherman Granite.

Anorthositic rocks comprise the bulk of the rock exposed in the complex. The principal occurrences of norite are: (1) along the northwest border of the anorthosite in association with hypersthene syenite, (2) within the strip separating the anorthosite into two masses, and (3) as an isolated body in the central portion of the northern anorthosite mass. Small norite bodies crop out within hypersthene syenite. The largest exposure of the hypersthene-bearing charnockitic variety of syenite is along the northwestern margin of the northern anorthosite mass and passes into hornblende syenite, called Red Mountain Syenite, to the north (Hodge and others, 1970; Smith and others, 1970). The granite that intrudes the anorthosite is part of the large Sherman Granite batholith which underlies most of the southern Laramie Mountains and portions of the Medicine Bow Mountains.

DENSITY DETERMINATION

Volumes of rock samples were measured with a Beckman (Model 930) air comparison pycnometer, and sample weights were measured on a Mettler (Type 415) balance. Volumes were repeated and the calibrated precision of specific gravity determinations is ± 0.005 g per cm^3 (Table 1).

BOUGUER GRAVITY ANOMALY MAP OF ANORTHOSITE COMPLEX

The Bouguer anomaly map (Fig. 2) over the anorthosite complex shows strong correlation with geologic features. The anorthosite is a gravity high, in contrast to the flanking sedimentary basins and younger Sherman Granite to the south, but is a gravity low compared to the older biotite and hornblende gneisses to the north. North of the anorthosite, anomalies over the older mafic gneisses reach a maximum of −110 mgal; this represents about a 40 mgal positive anomaly with respect to the −150 mgal values in the anorthosite. Strong positive anomalies occur over hornblende syenite and hypersthene syenite that border the anorthosite on the north and west. The positive-anomaly ridge over the hypersthene syenite continues south across the sedimentary rocks and then strikes eastward over the gneisses and associated norite-hypersthene syenite separating the two anorthosite bodies. The strong gravity gradients on the eastern border of the anorthosite reflect the fault-produced density contrast between sedimentary rocks of the basin and the crystalline rocks.

TABLE 1. ROCK DENSITIES

Rock type	Number of samples	Density range g per cm^3	Mean density g per cc
Granite	15	2.65 to 2.68	2.67
Hypersthene syenite	24	2.69 to 2.88	2.74
Hornblende syenite	29	2.70 to 2.78	2.73
Anorthosite rocks	36	2.71 to 2.88	2.76
Norite	7	2.98 to 3.10	3.05

Hypersthene Syenite Gravity Field

A gravity ridge located over the hypersthene syenite includes three distinct gravity highs. Bouguer anomaly values over the anorthosite adjacent to the hypersthene syenite fall to about −135 mgal, a 20 mgal positive anomaly. Gravity differences as great as 10 mgal with gradients of 3 mgal per km occur within the hypersthene syenite. The trend of the anomalies over the syenite crosscuts the geologic contacts. There is no apparent correlation of the gravity pattern with the distribution of surface densities (Hodge and Mayewski, 1969). At the southern end of the hypersthene syenite, the gravity ridge crosscuts the geologic contacts and is positioned over a small outcrop of norite.

Red Mountain Hornblende Syenite Gravity Field

Bouguer anomaly values over the hornblende syenite reach −125 mgal contrasted to the

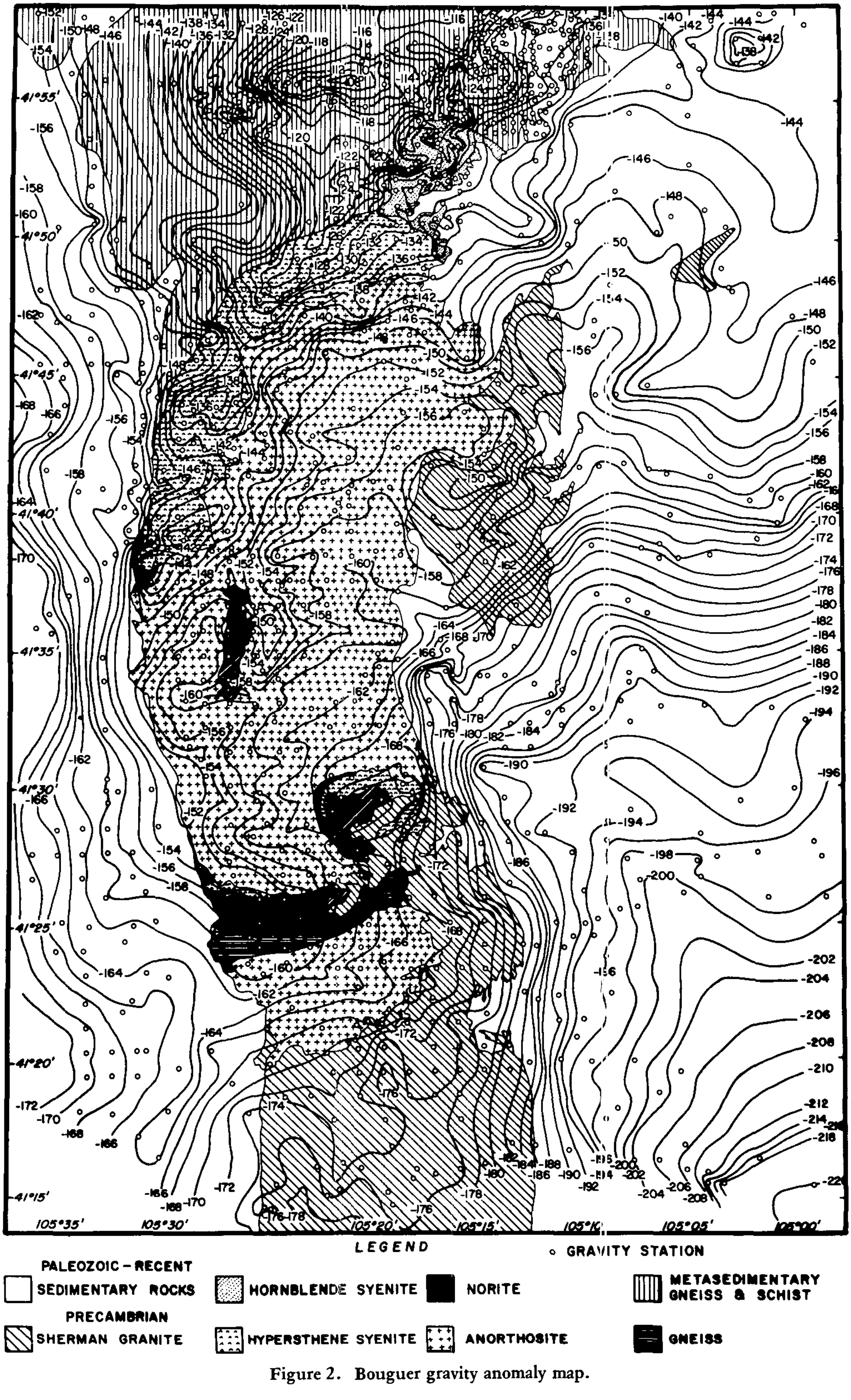

Figure 2. Bouguer gravity anomaly map.

−155 mgal values over the nearby anorthosite and resemble the gravity field over the hypersthene syenite. The gravity ridge over the hypersthene syenite extends over the southern part of the hornblende syenite but the maximum values are positioned over the contact of hornblende syenite and biotite-mafic gneisses. In this syenite are short-wavelength digitate positive anomalies up to 6 mgal that trend eastward perpendicular to the contact and trend of the country rock. The hornblende syenite gravity field is distinctive in its high over-all anomaly values and small wavelength anomalies within the body.

Anorthosite Gravity Field

The gravity field over the exposed anorthosite is regular and does not show any of the prominent highs that characterize the bordering geologic rock bodies. A small irregular anomaly within the anorthosite near 41° 35′ N. lat, 105° 25′ W. long crosscuts outcrops of norite. The gravity field over the two anorthosite bodies is separated by a 6-mgal gravity ridge located over norite-hypersthene syenite-gneiss rocks. Isoanomaly lines over the southern anorthosite trend eastward and presumably reflect the parallel east-trending density contrasts of the Sherman Granite and norite-hypersthene syenite. A similar trend continues westward over the Laramie Basin toward Laramie.

REGIONAL BOUGUER GRAVITY ANOMALY

Before interpretation, regional gravity variations must be removed from the Bouguer gravity anomalies. The major structural features of Wyoming are a pattern of alternating sedimentary basins and Precambrian crystalline ranges, and the Bouguer map of Wyoming shows strong correlation with the surface geology. Over sedimentary basins, the Bouguer anomaly values are strongly negative compared to the Precambrian crystalline areas. Strange and Woollard (1965) suggested that the regional gravity field strikes northwest and slopes gently (0.5 mgal per km) to the southwest in the vicinity of the anorthosite complex.

RESIDUAL BOUGUER GRAVITY

The residual gravity anomaly map (Fig. 3) represents the difference between the Bouguer gravity anomalies and the regional gravity anomalies. Subtraction of the regional anomalies has very little effect on their shape. The regional trend dips southwest (Hodge, 1966a) with a gradient approximately 0.5 mgal per km. A datum of −175 mgal which occurs over the Sherman Granite was used as a base to subtract the regional effects from the Bouguer values.

INTERPRETATION

Two-dimensional gravity models were computed with a Fortran IV computer program modified after Talwani and others (1959). The length-to-width ratio of most bodies within the Laramie anorthosite complex is greater than 4:1 so that significant errors should not be introduced by a two-dimensional approximation. Figure 3 shows the location of all profiles discussed in this section. In all models, the background density is assumed to be granite (2.67 g per cm^3).

The relations between Sherman Granite and anorthosite is shown in profile A-A′ (Fig. 4). The computed model indicates that the thickness of the southern anorthosite mass is about 4 km. The rocks that separate the northern from the southern anorthosite mass are probably no more than 1 km thick. The exact geometry of the Sherman Granite–anorthosite contact and the shape of the "norite" may be different since by changing the geometry of the norite, a different contact geometry for the granite and anorthosite is necessitated and vice versa. The conclusion that Sherman Granite overlaps the older anorthosite seems inescapable judging from the shape and position of the gravity anomaly. If a mean gravity difference of 16 mgal between Sherman Granite and anorthosite is used, a thickness of slightly over 4 km is indicated for anorthosite against Sherman Granite from the attraction of a Bouguer slab. Inherent in the calculation of the models is the assumption that the models show only the thickness of a density contrast. No gravity interpretation can prove whether the Sherman Granite underlies the anorthosite or anorthosite underlies the Sherman Granite. From a geologic view, it is more reasonable for the younger Sherman Granite to underlie the anorthosite.

The thickness of a rock body that crops out is roughly proportional to the horizontal distance over which a gravity anomaly falls to one-half of its maximum value. By employing the half-width estimates, a minimum density contrast may be computed. The relation

$$H > 23.9 \quad \Delta G \max / Q_{\min}$$

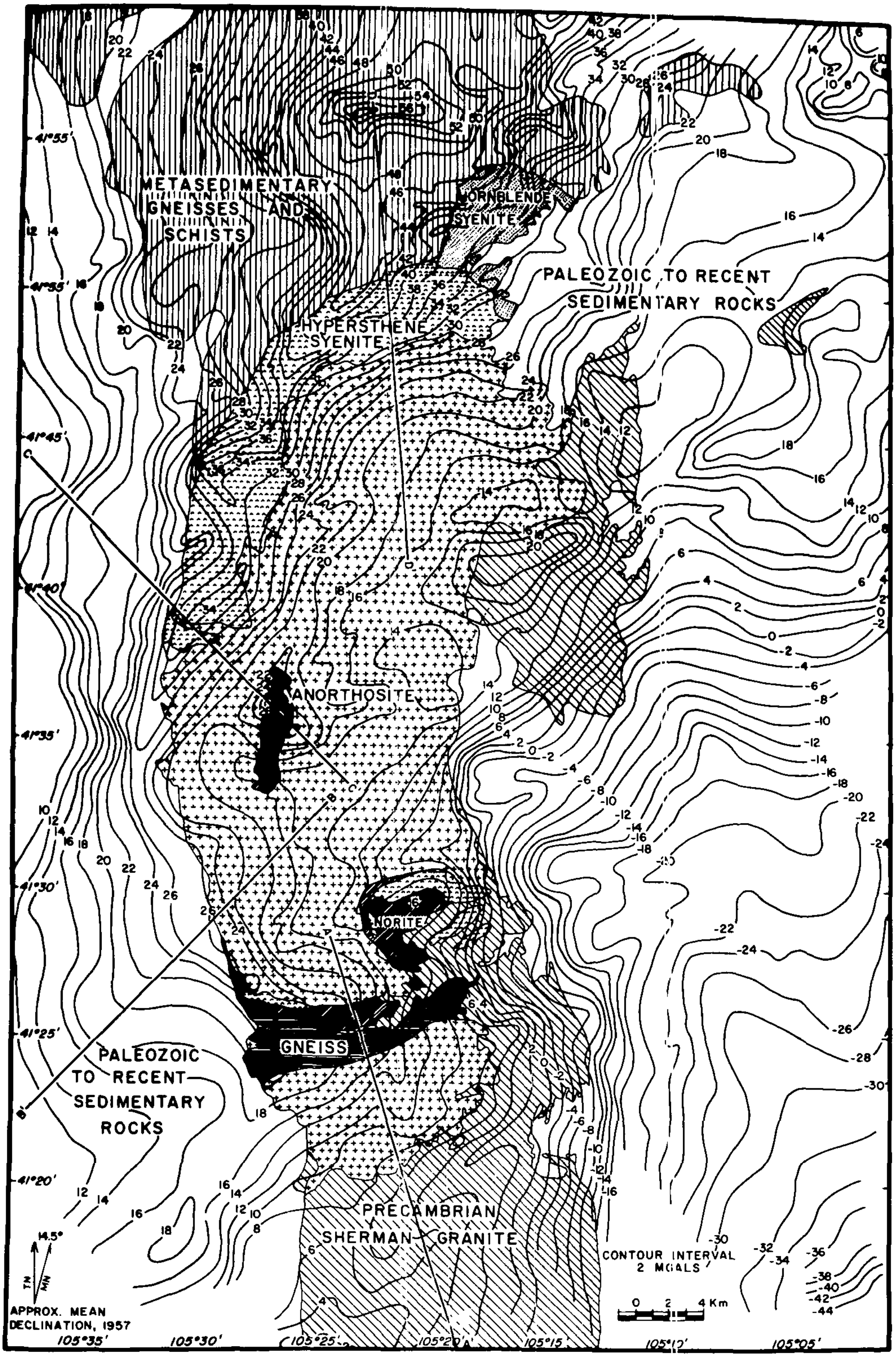

Figure 3. Residual Bouguer gravity anomaly map. Profiles for gravity interpretations shown in Figures 4 to 7 are marked.

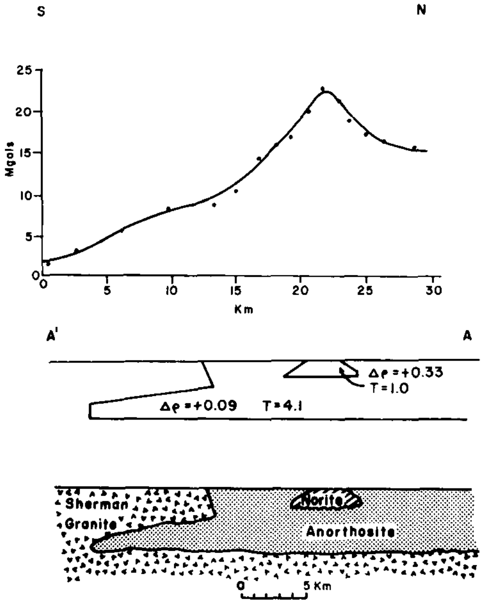

Figure 4. Gravity profile A-A′ across anorthosite and Sherman Granite. Dots are calculated attraction of the gravity model. Figure 3 gives location of profile.

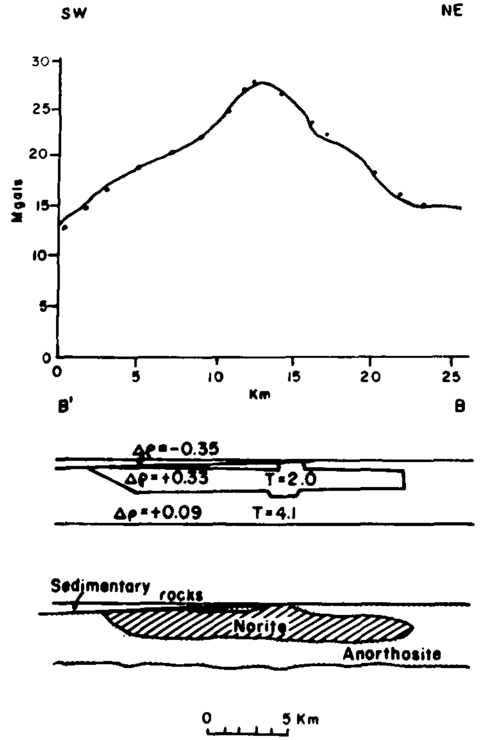

Figure 5. Gravity profile B-B′ from anorthosite into Laramie Basin.

will yield the minimum density contrast between two bodies (Parasnis, 1966). G_{max} is the maximum observed gravity difference, Q_{min} is the minimum density contrast, and H is the depth. A minimum density contrast of 0.13 g per cm^3 is computed for the rocks separating the two anorthosites. The density estimated in this manner gives a value of 2.88 g per cm^3 for the disturbing rocks. This high estimated density indicates that the anomaly is most likely caused by norite, which has a density of about 3.00 g per cm^3.

The residual gravity along the western margin of the southern anorthosite mass suggests that a westward continuation of anorthosite underlies the portion of the Laramie Basin near 41°23′ N. lat, 105°30′ W. long. In Figure 5 (B-B′), a subsurface mass of anorthosite overlain by a norite body is shown buried under a cover of about 0.3 km of sedimentary rocks. The thickness of the norite mass varies between 1 to 2 km; the anorthosite is a uniform layer 4.0 km thick.

Figure 6 (C-C′) depicts the relation of anorthosite and syenite in the northwest part of the complex. If the syenite is assumed to be the disturbing mass and if half-width depth estimates are employed, then a minimum density contrast of 0.33 g per cm^3 is found to exist to a depth of at least 3.5 km beneath the southern end of the syenite pluton. The observed density contrast cannot be due to hypersthene syenite because its measured density (2.74) is too low. Gravity anomalies over the syenites are far too high in view of the low relative density of syenites; therefore, a high-density mass exists beneath the syenite. Maximum depth to the top of the disturbing mass is 2.5 km from maximum depth calculations (Bott and Smith, 1958). Smith (1967) and Hodge and Mayewski (1969) suggested that norite underlies syenite to explain the observed gravity anomaly. The gravity model shown in Figure 5 also indicates that an isolated norite body (1 km thick) in the northern anorthosite mass is not connected to the primary dense mass beneath the syenite to the west.

Profile D-D′ (Fig. 7) extends across the anorthosite syenite contact and into the gneisses in the northern part of the complex. There is no way to distinguish between the two syenites gravitationally because their densities are almost identical. In this area, the dense

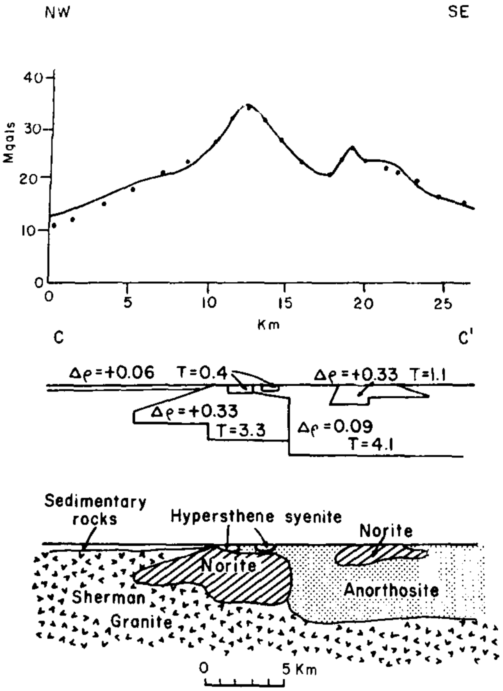

Figure 6. Gravity profile C-C′ from anorthosite into syenite. High gravity values over syenite must be explained by a mass surplus underlying syenite.

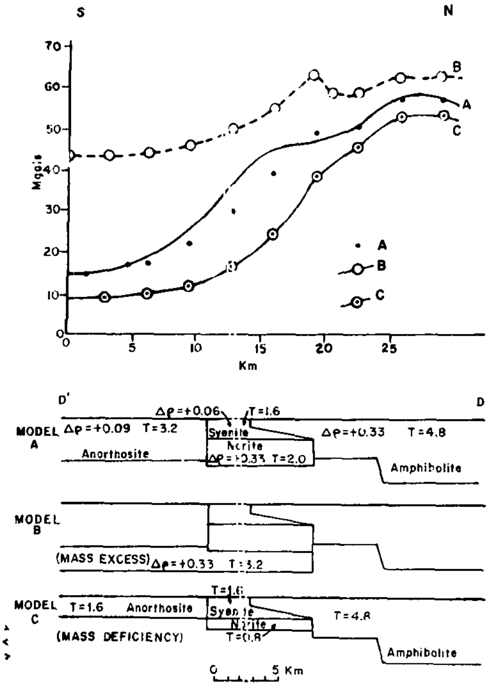

Figure 7. Gravity profile D-D′ through northern part of anorthosite complex. Different mass relations are postulated and their gravitational attraction compared with observed gravity values. Models show that large amounts of dense mafic differentiates under anorthosite are not plausible.

mass (norite) is about 2.5 km thick, and the calculated thickness of both syenites is 1.5 km (Fig. 7, model A). Although models may be varied somewhat, according to these models the "norite" would have about two to three times greater mass than the syenites.

Profile D-D′ (Fig. 7) can be employed along with geologic evidence to determine the probability for the existence of an anomalous mass beneath anorthosite. The anorthosite is a gravity low with respect to gneisses. Models B and C (Fig. 7) illustrate the anomalies to be expected from mass excesses and mass deficiencies, respectively, within the anorthosite complex. In the first model, a denser, mafic mass 2.4 km thick, is placed beneath anorthosite and norite layers at depths ranging from 3.2 to 4.0 km, respectively. The resulting gravity anomalies far exceed the observed gravity anomaly. The second model results in an anomaly that is insufficient with respect to the observed anomaly. Model A illustrates probable mass distributions and geometries that can satisfy the observed gravity anomaly. It should be noted that the presence of the norite cannot be uniquely defined because norite has approximately the same density as amphibolite. Contacts between the two bodies cannot be distinguished. Model A is based on the observed geologic relations and mass distributions inferred. In all probability, there is no large subsurface mafic mass beneath the Laramie anorthosite complex, and the inferred mass distributions and geometries are plausible estimates.

A regional profile A-B-C (Fig. 8) has been constructed through the anorthosite complex from the granitic gneiss complex on the north to the Sherman Granite on the south. The profile strengthens the conclusion that no large amounts of mafic differentiates are associated with the anorthosite. A three-dimensional model of the inferred mass relations is shown in Figure 9.

MASS DISTRIBUTIONS OF OTHER ANORTHOSITES

Considerable differences are found in the gravity fields and mass distributions of the layered and massif-type anorthosites. Simmons's

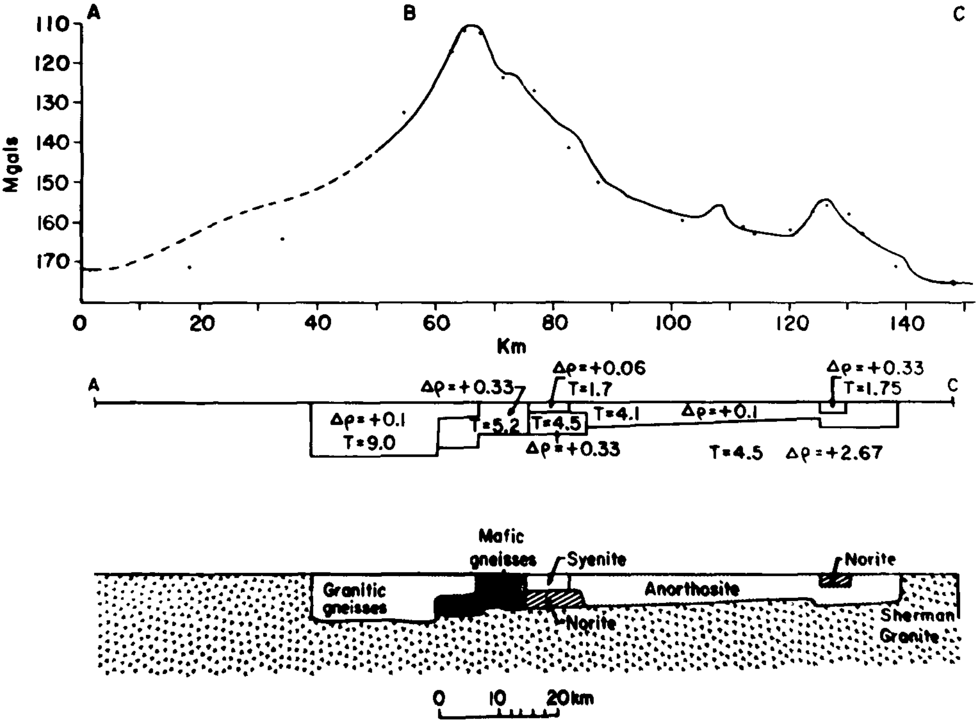

Figure 8. Gravity profile A-B-C across entire anorthosite complex. Position of profile is marked on Figure 1. Gravity values at north end of profile are interpolated and are very approximate.

(1964) study on the Adirondack anorthosite shows a 15 to 20 mgal negative anomaly over the main anorthosite occurrence. Similar 15 to 20 mgal gravity lows are reported over the Morin, Lake, St. Jean, and St. Urbain anorthosite massifs in Quebec by Thompson and Garland (1957). The Egersund anorthosite complex in Norway shows no anomaly except for a positive anomaly over noritic rocks in a trough through the anorthosite (Geographical Survey of Norway, 1961). These gravity anomalies strongly suggest that dense rocks do not floor these massifs. In contrast, the gravity anomaly over the Stillwater complex, which is composed of approximately equal amounts of anorthosite and mafic rocks, shows about a 13 mgal positive anomaly (Bonini, 1969). The Lake Superior (Duluth) complex is generally a positive anomaly (Ikola, 1968). We can generalize that, disregarding the gravitation attraction of the younger less dense granites, the Laramie anorthosite represents a gravity low with respect to enclosing metasedimentary country rocks; this relation is similar to other massif-type occurrences. The distinguishing feature, perhaps, is the peripheral gravity highs that partially surround this anorthosite.

PARENT MAGMA

Estimates of the parent magma of most anorthosite massifs vary significantly depending on whether the estimator believes the syenites are comagmatic. Those investigators that include the syenites and granites as part of comagmatic series suggest composition such as diorite (Balk, 1931), quartz diorite (Green, 1969), granodiorite (Barth, 1933; Philpotts, 1966), or basalt (Bowen, 1917). Buddington (1939), who does not associate the syenites with the anorthosites, envisioned a gabbroic anorthosite magma as the parent rock.

Recent strontium and oxygen isotopic evidence (Epstein and Taylor, 1967) from numerous anorthosite occurrences suggests that parental magma was a derivative of a basaltic magma. Experimental results (Lindsley, 1966) on the system albite-anorthosite-diopside indicate that this system cannot provide an adequate model for generation of anorthosite magmas at pressures found in the crust. More recent experimental work on a sample of chilled margin from the Michikaman intrusion (Emslie and Lindsley, 1968) showed that at pressures above 12 kb (40 km) fractional crystallization of clinopyroxenes would selectively enrich magma in alumina and soda. Selective enrichment of these components is necessary for the genesis of anorthosite magma. Partial melting of the mantle at these conditions would likewise produce the parent magma. There seems to be general agreement that anorthosites are initially derived in the upper mantle, but the nature of the original parent rock, the limited occurrence of anorthosites, and possible contamination during magma migration are poorly understood.

Volume estimates for each of the major rock types comprising the anorthosite complex can be made from the gravity data. The total surface area of each mass is obtained from the geologic map of the complex and corrected in instances when gravity evidence for subsurface lateral extensions is present. Minimum volume estimates are computed by multiplying total surfaces areas by average depths derived from gravity model calculations. The volume estimates are minimums because of the uncertainty in fixing exactly the loss by erosion since emplacement and are also limited by the restrictions of gravity interpretation. The reliability of conclusions is a function of the precision of depth and volume determinations which can be varied within certain limits.

The resulting minimum mass for the respective rock types are: anorthosite, 9.7×10^{18} g; norite, 2.3×10^{18} g; and syenites, 6.0×10^{17} g. If we assume that the syenites are comagmatic, then anorthosite, norite, and syenite constitute 78, 17, and 5 percent by volume, respectively. Using estimates of these volumes and the average chemical compositions of the respective rock types (Nockolds, 1954), the average chemical composition for the anorthosite complex approximates a typical noritic anorthosite. The composition of the parental magma does not change much if the syenites are not considered as part of the comagmatic phases. Figure 9 illustrates the major mass distributions and geometric relations.

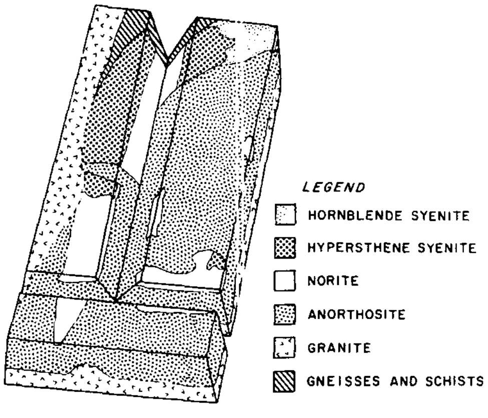

Figure 9. Three-dimensional drawing of Laramie anorthosite complex. Geometry and mass distribution are shown.

Emplacement and Differentiation of the Anorthosite Complex

The stages in the life of a magmatic pluton might be separated in a sequence of stages including generation, upward transfer, differentiation, and solidification. The gravity study gives three-dimensional information as to the latter two processes. Numerous authors (Bowen, 1917; Miller, 1929; von Eckermann, 1938) have suggested that anorthosite massifs have differentiated from a gabbroic parent. Crystallization of a gabbroic magma could produce: (1) ultramafic and mafic base; (2) anorthosite; (3) relatively undifferentiated sequence; and (4) granite at the top. Simmons (1964, p. 91) calculated a 50 mgal positive anomaly for the attraction of a differentiated gabbroic magma the size of the Adirondack anorthosite. Since the Adirondack anorthosite massif is a negative anomaly, this geometry seems unlikely. The negative anomaly over the Laramie anorthosite likewise suggests that differentiation in situ (or in the middle or upper crust) of a gabbroic magma is improbable.

The general relation commonly found in anorthosite massifs is illustrated by the Laramie anorthosite where the base or core is composed of anorthosite followed in sequence by layers of norite, syenites, and granites at the top, which suggests that there is a gravitational settling operative in at least part of the crystallization process. If massif-type anorthosite formed from a calc-alkali parent magma (Philpotts, 1966) rather than a more mafic gabbroic type, then gravitational settling of early formed plagioclase might take place. Bottinga and Weill (1970) showed that the calculated magmatic liquid density for a typical calc-alkali series (Mt. Shasta) varies from 2.44 g per cm^3 for hornblende andesite to 2.63 g per cm^3 for olivine basalt at 1100°C. The density of plagioclase primocrysts with composition of 50 percent anorthite would be about 2.63 g/cc at these temperatures. These density estimates indicate that plagioclase will settle and not float through liquids of the calc-alkali series. Therefore, initial crystallization of plagioclase at the liquidus would likely produce an accumulate layer of plagioclase at the base of the intrusion. Subsequent simultaneous crystallization of pyroxene and plagioclase could progressively produce the noritic anorthosite and then norite. Finally syenites would be formed. This sequence of layers once nearly solidified is a gravitationally unstable configuration since norite is more dense than anorthosite.

The primary layering is basically envisioned to be a result of magmatic crystallization, but, due to the unusual density inversion in the sequence of layers, secondary movement of the complex is possible. The domal structure of the anorthosite complex could be explained as a subsequent rise of the anorthosite mass due to gravitational instability resulting from (1) the primary density distribution, and (2) the surrounding dense country rocks. As a consequence of gravitational instability of the primary layering and overlying dense country rocks, anorthosite would tend to migrate upward through the center with denser norite moving downward along the borders. Ramberg's (1967, p. 324) centrifuge scale-model experiments simulate the kind of response to this gravitation instability that might be expected. Ramberg showed that after a relatively short run in the centrifuge the heavy layer drapes over the rising, less dense material. The viscosity contrasts used in the experiments simulate plastic and not liquid flow of material. If the process were stopped at this stage, the mass distribution would simulate the mass geometry common to intermediate-type anorthosites. After a longer run in the centrifuge, Ramberg shows that the heavy layer separates and migrates downward to an equal-density stratum. Martignole and Schrijver (1970) suggested a similar process for evolution of the Morin anorthosite complex. It seems that the ability of the dense layers to subside and less dense layers to rise within the enclosing media, presumably a function of rigidity of the enclosing envelope and conversely the depth of emplacement, might explain the different mass geometries of the anorthosite types.

Geologic field evidence that would support this emplacement mechanism for the Laramie anorthosite is not conclusive, although Newhouse and Hagner (1957) showed that foliation within the norite bodies dips away from the anorthosite and that an antiform is defined by well-developed foliation and layering within the anorthosite. This is the structural geometry that would be expected of a rising dome. The highly developed foliation within the anorthosite also seems to indicate that considerable movement has taken place in the anorthosite after the crystallization of much of the complex.

CONCLUSIONS

Gravity data indicate that the Laramie anorthosite complex consists of a core of anorthosite surrounded by partial layers of norite and syenite. The selected profiles and gravity models over the syenites on the northwestern flank of the anorthosite show that the syenites are floored by a dense rock. Because noritic rocks can reach a density of 2.95 g per cm^3, norite is the most likely rock type causing this positive anomaly. The positive anomaly wraps around the northern rim of the anorthosites; it terminates over the younger Sherman Granite to the east. The norite reaches a maximum thickness of 2.4 km in the north and thins to about 0.8 km on the southeastern flank of the northern anorthosite body.

Analysis of the gravity field over the syenites suggests that norite floors the syenites, but this is not a unique solution to the gravity data. Dense country rocks adjacent to the hornblende syenite make interpretation more ambiguous, but the conclusion is inescapable that syenites are underlain by large amounts of dense rock. However, since the country rocks adjacent to the hypersthene syenite are principally granite gneisses, the possibility of incorporated dense country rocks causing the strong positive anomalies is remote (Hodge and others, 1970). The trend of the broad wavelength positive anomalies is parallel to the configuration of the anorthosite and perpendicular to the trend of the gneisses.

The gravity interpretation of the anorthosite indicates that it is a slab 4 to 5 km thick. Small anomalies within the anorthosite can be accounted for by rootless bodies of norite and minor undulations in the subsurface shape of the floor of anorthosite. Significant quantities of mafic material to suggest in-place differentiation of basalt are not present at the base of the anorthosite.

Although several different types of parent magmas have been suggested by various workers, the relative masses of rock types from our gravity interpretation suggest a noritic anorthosite parent magma, and basaltic magma must be ruled out. The following sequence of events may have led to the origin of the Laramie anorthosite complex. A primary noritic anorthosite magma, derived from partial melting of rocks in the upper mantle, intruded the lower crust. The magma rose until it reached a level of intensely metamorphosed sedimentary rocks at depths of approximately 20 km or greater. The magma spread laterally and began to crystallize. Early crystallization of plagioclase resulted in a gravitationally unstable layer of anorthosite overlain by denser norite. The complex did not crystallize completely, but consisted essentially of a crystalline mush lubricated by interstitial residual fluids, which could have been water rich (Yoder, 1969). The anorthosite continued to rise as a diapiric intrusion through the overlying norite layer (Ramberg, 1967) and domed its own differentiates as well as the overlying country rocks. As this occurred, the denser norite layer flowed plastically downward at the margins of the diapir. Residual liquids also migrated toward the marginal zones, ultimately crystallizing as syenites. Final crystallization resulted in a central core of anorthosite surrounded by layers of norite and syenite (which crystallized from the residual liquids). The structural geometry was preserved as a primary feature which originated in consequence of the plastic flow of the various layers.

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APPENDIX 1. GRAVITY MEASUREMENTS

A reconnaissance gravity study over the southern Laramie Range by Hodge (1966a) defined the gross features of the anorthosite complex. Detailed gravity studies of parts of the complex include those by Woodfill (1968, 1970; Squaw Rock granite gneiss and syenite), Smith (1967; syenite and anorthosite), and Hodge and Mayewski (1969; hypersthene syenite). The work in the northern part of the area has been reported in Hodge and others (1970) and Smith and others (1970). The station data from these surveys is compiled in the over-all Bouguer map of the anorthosite complex. Bothner (1969) studied the gravity field over the Sherman Granite to the south of the complex.

Gravity stations were established with a Worden Master gravimeter at bench marks, surveyed section corners, or spot elevations. Vertical control at bench marks and section corners is precise to within 0.02 and 2 ft, respectively. In areas of no vertical control, a pair of 0 to 15,000 ft aneroid altimeters were used for relatively few stations. The precision of these stations is within 10 to 15 ft. Horizontal control was provided by U.S. Geological Survey topographic maps (scale 1:24,000, and scale 1:62,500).

About 1,100 gravity stations were established with station spacing of 0.5 to 3 mi over the crystalline rocks and 1 to 6 mi over the sedimentary basins. Gravity reductions were computed, based on a Bouguer density of 2.67 gm/cc, in accordance with procedures outlined by Dobrin (1960). Terrain corrections were computed by Hammer's (1939) method. The maximum terrain correction computed was 1.55 mgal, but most stations had corrections less than 0.5 mgal. The network of base stations was tied to the world-wide grid of gravity stations (Woollard and Rose, 1963) at the Cheyenne Municipal Airport, Wyoming. Error (standard deviation) of the Bouger anomaly values is 0.8 mgal or less.

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