A gravity and magnetic study of the Skalkaho pyroxenite-syenite complex western Montana

Hollice Andrew Snyder

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A GRAVITY AND MAGNETIC STUDY
OF THE
SKALKAHO PYROXENITE-SYENITE COMPLEX, WESTERN MONTANA

by
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B.A., University of Montana, 1983

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for the degree of
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University of Montana
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Chairman, Board of Examiners
Dean, Graduate School
Date

March 21, 1986
The aim of the study was to gain an impression of the subsurface configuration of the Skalkaho (mafic-alkaline) Complex, east of Hamilton, Montana. This was accomplished through the integration of geologic information and the results of forward modeling of gravity data. In the modeling process, the pyroxenite core was delineated with respect to the out-lying syenites and host rocks.

The mid-Cretaceous Skalkaho Complex intruded the mid-Proterozoic Wallace Formation of the Belt Supergroup. The metasedimentary host rocks are situated within the western or trailing edge of the allochthonous Sapphire Tectonic Block, which postdates the complex. The pyroxenite-syenite intrusion was shallowly-emplaced, probably as a co-magmatic, immiscible system. The complex covers about 9 sq. km, with an oblong, east-west trending core of pyroxenites surrounded by two syenite bodies that lack nepheline. Pyroxenite-syenite contacts range over 600 meters of elevation difference. A small, massive carbonate body composed mainly of calcite probably post-dates the complex and is not carbonatite. The remarkably similar, contemporaneous Rainy Creek Complex is 275 km to the north near Libby, Montana, but most likely had a magma source independent to that at Skalkaho.

Bouguer anomaly values ranged from -169 to -185 milligals over the area, with the highest anomalies centered over the pyroxenites. Modeling profiles perpendicular to the longitudinal trend of the complex show that the pyroxenite body is shaped like a narrow, inward-dipping cone which thins from east to west, and not a sill or outward-dipping cone. Approximate depths for the pyroxenite range from 1000 to 200 meters east to west. The syenite bodies formed along the flanks of the pyroxenite, but some syenite may have capped the pyroxenite at the time of emplacement. The Skalkaho intrusion probably is a "cored" complex, much like the ring-dike complex at Magnet Cove, Arkansas.

The irregular distribution of magnetite within the irregularly-distributed Skalkaho rock units complicated the use of magnetic survey data to complement the gravity results. Magnetic susceptibilities varied from 0.000023 to 0.0051 cgs units, which correspond to volume percents of magnetite from less than 0.01 to 3.0. Total field intensities ranged from 54,000 to 66,000 gammas and gradients of several thousand gammas per 30 meters were common.
ACKNOWLEDGEMENTS

Sincere thanks goes to Steve Sheriff and Don Hyndman for strengthening my insights into geophysics, structure and igneous petrology and I appreciate the efforts of Dave Alt, Wayne Van Meter and Tom Margrave, who also sat on my committee. I especially wish to thank Marty White of Western Vermiculite Co. for generous support of my project. Sigma Xi also provided assistance. Vicki Bankey of the U.S.G.S. Geophysics Division, Denver aided in the reduction of the gravity data and Garry Carlson, my friend and business partner, often helped with the computer work.
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INTRODUCTION

Purpose

The aim of this study is to gain an impression of the subsurface configuration of the Skalkaho Igneous (pyroxenite-syenite) Complex. This was accomplished through the integration of geologic information and the results of forward modeling of gravity data. In the modeling process, the pyroxenite core was delineated with respect to the out-lying syenites and host rocks. The densities of the syenites and host rocks are nearly the same and do not allow sufficient density contrast to analytically model the syenites. The similar Rainy Creek Complex is relatively nearby and is compared.

Location, Access, and Topography

The moderately exposed Skalkaho mafic-alkaline intrusion covers approximately 9 square km. It is at the head of the St. Clair Creek drainage near the west slope of the southern Sapphire Range, about 33 km east-northeast of Hamilton in western Montana (Figure 1).

Access is good via a U.S. Forest Service road from the Willow Creek drainage to the north and by a private road from the Bitterroot Valley to the west. Lateral logging roads provide limited access within the area. Due to snow conditions, travel is often restricted between October and May. Also, numerous fallen trees hinder off-road travel. The topography is rugged and elevations range from 1770 meters along St.
Clair Creek to 2580 meters at Skalkaho Mountain, the highest point in the Sapphire Range.

Previous Related Work

Lelek (1979) detailed the lithologies in the Skalkaho Complex and made an admirable case for the role of liquid immiscibility in the formation of the intrusion. The Rainy Creek Complex (Boettcher, 1967) is similar to that at Skalkaho (Lelek, 1979). The Rainy Creek Complex is 275 km to the north near Libby in northwestern Montana. However, Boettcher (1967) proposed a sequential magmatic system for the igneous bodies, as opposed to the co-magmatic, contemporaneously-emplaced system formulated by Lelek (1979). La Tour (1974) examined metamorphism and scapolite growth in metasediments in an area directly south of the Skalkaho Complex. Presley (1970) reported on igneous and metamorphic petrology in the Willow Creek area in the drainage directly to the north. Hyndman and others (1975) and Hyndman (1980) reported that the metasedimentary host rocks for the Skalkaho Complex comprise a portion of an allochthonous tectonic block.
Regional Setting

The Skalkaho Complex intruded the calc-silicate/quartzose, mid-Proterozoic Wallace Formation of the Belt Supergroup (La Tour, 1974). The host rocks lie within the western or trailing edge of the allochthonous Sapphire Tectonic Block. The block measures about 70 km east-west and 100 km north-south and it consists mainly of Belt Supergroup metasediments. Hyndman (1980) suggested that the block was transported on an infrastructure of autochthonous Belt units along a mylonite detachment zone and off-loaded from west to east during intrusion of the Idaho Batholith, some 75-80 million years ago during the late Cretaceous. Exposures of the batholith make up the bulk of the Bitterroot Range, beyond the Bitterroot Valley west of the study area. The mylonite zone is well exposed along the east slope of the Bitterroots. Based on Hyndman's (1980) data, I estimate the detachment zone to be about 6 km below the surface at the Skalkaho Complex. West-dipping thrust faults resulting from the tectonic movement are evident near the leading or eastern edge of the Sapphire Tectonic Block (Hyndman, 1980), but Garmezy and Sutter (1983) proposed that movement instead probably occurred along a reactivated detachment zone in an extensional environment during Eocene time, some 45 million years ago.
The Rainy Creek Complex was also emplaced into calcareous Wallace Formation metasediments (Boettcher, 1967) that are allochthonous (Harrison et al., 1980). The disturbed zone comprises mainly west-dipping thrust faults and folds that developed no earlier than 72 million years ago. As with the Sapphire Block, the Rainy Creek host rocks were disturbed for the most part by accretionary tectonism, that developed from the west in the Cordilleran thrust and fold belt extending south from Alaska into Mexico (Mudge, 1982).

Local Geology

I remapped the area at a larger scale to improve on Lelek's (1979) work and to provide better control for modeling purposes (see Figure 2). The pyroxenite contacts were changed little, whereas the syenite and the late Cretaceous granodiorites (Presley, 1970) of the Willow Creek basin along the northern fringe of the complex were better delineated. A pi diagram (see Figure 3) of poles to host rock bedding from the relatively few attitudes that could be measured around the complex, reveals that most likely only minor doming occurred due to intrusion. Presley (1970) reached a similar conclusion for the same metasedimentary rocks directly to the north. Also, I did not find any evidence of a penetrative fabric in the Skalkaho intrusion, nor did Lelek (1979). Rock dating (discussed later) shows that the complex predates the Sapphire Block. Therefore, I conclude that the Skalkaho Complex has not been deformed since intrusion, even though it has been transported to the east.
FIGURE 3: PI DIAGRAM FOR HOST ROCK BEDDING
The Skalkaho intrusion was emplaced in the upper few kilometers of the crust (Lelek, 1979). The oblong pyroxenite body is surrounded by two syenite bodies along the pyroxenite margin. The pyroxenite is exposed at elevations between 1900 and 2500 meters. Lelek (1979) did an excellent job of delineating the lithologies, which include irregularly-distributed mica, amphibole, and anhydrous pyroxenites. The coarse mica (mostly biotite) pyroxenite is the most abundant variety, whereas the anhydrous pyroxenite is the least. The fine-grained anhydrous unit consists almost entirely of salitic pyroxene. The fine to coarse-grained amphibole pyroxenite is the most variable and contains the most of the common accessory minerals (apatite, magnetite, sphene) in the pyroxenites (Lelek, 1979).

Two small masses of biotite, hydrobiotite, and vermiculite concentrations within the pyroxenite have been partially developed by the Western Vermiculite Company of Victor, Montana. Syenite and alkali syenite (but no nepheline syenite) with accessory pyroxene, mica, and amphibole make up the fringe felsic unit (Lelek, 1979). Since the syenites are exposed at elevations about as low and high as those of the pyroxenites, syenite probably exists at depth along the flanks of the pyroxenite.

Two relatively small outcrops of trachyte are associated with the syenites and a small exposure of pegmatite (feldspar and pyroxene with garnet, sphene, and apatite) is associated with pyroxenite. Several narrow quartz-calcite hydrothermal veins cut the complex (Lelek, 1979). Such veins are common in the Sapphire Range. Another variety of
carbonate is intriguing. A vug-less, dike-like, door-sized exposure contains massive medium to coarse-grained calcite with a fibrous amphibole, and is encased by pyroxenite, but does not show sharp contacts with it. The above characteristics argue against hydrothermal, inclusive, or rheomorphic origins (Lelek, 1979).

The Skalkaho and Rainy Creek complexes are remarkably similar. The similar size, pyroxenite varieties and distribution of pyroxenite, varieties of syenite, pyroxenite-syenite juxtaposition with a pyroxenite core, an elevated, fringe syenite body, and trachytic and pegmatitic occurrences bear this out. Even a pyroxenite-hosted occurrence of vermiculite, which has been successfully developed by W.R. Grace Company, exists at Rainy Creek.

The major differences at Rainy Creek are: 1) the pyroxenite and syenite bodies are circular in nature, 2) a small, poorly-defined exposure believed to be altered nepheline syenite exists just outside the intrusion, and 3) the complex lies in a syncline and may well have been deformed subsequent to emplacement (Boettcher, 1967).

A rubidium/strontium date by Boettcher (1967) put the Rainy Creek Complex age at 94 million years. \(^{87}\text{Sr} / {^{86}\text{Sr}}\) isotopic compositions of the syenites and pyroxenites at Skalkaho and Rainy Creek define an age of 106.7 \(\pm\) 16 m.y. or mid-Cretaceous, for both complexes along a combined isochron. \(^{87}\text{Sr} / {^{86}\text{Sr}}\) isotopic ratios range from 0.7035 to 0.7082 (Futa and Armbruchmacher, 1983). Large variations in rubidium and strontium concentrations for each complex, strontium and neodymium isotopic ratios, and trace element concentrations suggest
independent sources for co-magmatic pyroxenite-syenite intrusions at Skalkaho and Rainy Creek (Futa and Armbrustmacher, 1983; Futa and Armbrustmacher, 1985). In any case, the dating shows that intrusion of both complexes occurred before they were tectonically-disturbed during the late Cretaceous.

Carbonate rocks from Rainy Creek considered by some to be carbonatites (carbonate rocks associated with alkaline intrusive activity) have significantly higher \(^{87}\)strontium/\(^{86}\)strontium ratios, generally higher strontium content, but about the same rubidium content as the syenites and pyroxenites. This suggests a source for the carbonate rocks different from that of the syenite and pyroxenite (Futa and Armbrustmacher, 1983). In simple terms, a typical carbonatite complex is a composite of nephelinitic, pyroxenitic, syenitic, and carbonate units with similar deep-seated origins (Hyndman, 1985; pgs. 362 and 404). Without any further evidence, I infer that the massive, dike-like carbonate material at Skalkaho also has an origin independent of the pyroxenite and syenite, and is therefore not carbonatite. Perhaps, the carbonate was somehow incorporated from the calcareous host rocks and then enclosed by and partly assimilated into the pyroxenite.
Gravity Data Acquisition

87 gravity readings were taken with a Worden Pioneer model gravimeter over the study area for an average of about 4 stations per square kilometer. 11 temporary base stations were established from an absolute gravity station at the Science Complex, University of Montana, Missoula, Montana. Survey circuits were completed over a maximum of three hours, but mostly in less than two. 17 survey stations were surveyed in from the west end to the complex core. Another 16 were established at U.S. Geodetic Survey benchmarks. The remaining sixty percent were located at landmarks such as road/stream intersections where elevations could be interpolated to within three meters from newer digitized topographic maps. The latter gave much better results than those obtained with an altimeter.

Density measurements in grams per cubic centimeter were taken from 46 representative samples and are tabulated in Table 1.

The composite average for the 26 out-lying syenite, metasediment, and granodiorite samples is 2.63. With the value of 3.26 for the pyroxenite core, the density contrast for modeling purposes is 0.63. The density contrast between the syenites and host metasediments (2.65 - 2.62 = 0.03) is insufficient to realistically model the syenitic portion of the intrusion because substantial terrain corrections (discussed later) were necessary.
Gravity Data Reduction

I compiled my gravity survey data on magnetic tape, which I sent to the Geophysics Division at the U.S. Geological Survey in Denver for reduction and calculation of Bouguer anomaly values. This service is available in a cooperative effort to collect gravity data in Montana. The Bouguer gravity anomaly compares the theoretical gravity (based on latitude) with that actually observed in the field and reduces the data to one datum plane. It includes corrections for the earth's curvature, the gravity station's elevation above datum (free-air correction), the mass between the station and the datum (Bouguer correction), and for the gravity effects of surface irregularities in the vicinity of the station (terrain correction) (Telford et al, 1976).
A program by Dansereau and Wahl (1979) was used at the U.S.G.S. to reduce gravity meter readings to observed values, taking into account earth-tide and linear meter drift. The theoretical gravity values calculated were based on the 1967 formula of the Geodetic Reference System. Complete Bouguer anomaly values were computed from a program by Godson (1978), which used Plouff's (1977) method to calculate the terrain corrections out to a radius of 166.7 km. These terrain corrections are based on digitized elevation data organized in 15-second compartments from 0 to 5 km, 1-minute compartments from 5 to 21 km, and 3-minute compartments from 21 to 167.7 km. My Bouguer anomaly map (Figure 4) with appropriate two milligal contour intervals is based on values calculated assuming an average rock density of 2.67 for the Bouguer and terrain corrections. Of course, interpolation based on a linear gradient was necessary at times when contouring the reduced gravity data on the map. Also, Figure 4 includes an inset showing the regional Bouguer anomaly setting for the Skalkaho Complex, based on Hassemer's (1984) work. Figure 5 shows the gravity station locations with corresponding Bouguer anomaly values. A listing of the reduced gravity data can be found in Appendix A.

Terrain corrections and elevation are the greatest sources of error in gravity surveys. An elevation difference of three meters would result in an error of 0.5 milligals (Telford et al, 1976). I checked the Bouguer anomaly calculations done by the U.S.G.S. Most particularly, I examined the terrain corrections. Using Hammer's (1939) method for terrain corrections for over ten percent of the
stations, I compared my results with those of the U.S.G.S. out to a radius of 895 meters or zone F, where terrain corrections are the most significant (Hammer, 1939). Differences ranged from 0.12 to 1.23 milligals, averaging 0.66 with a standard deviation of 0.41. For similar surveys, Cantwell (1980) and Gary (1980) had probable error estimates (as one standard deviation) of 0.45 and 0.1 milligals for terrain corrections using Hammer's method and gravimeter temperature variations, respectively. For my survey, I estimate probable error for interpolation of gravity values while contouring the Bouguer anomaly map to be 0.5 milligals. Taking the above sources of error into account, the total estimated error ($\sqrt{\sum \delta^2}$) is 0.93 milligals, which is consistent with that for Gary's (1980) survey.

Results of Gravity Interpretation

The forward modeling program used for this project is GRAV1, from the Geology program library at the University of Montana. A copy of GRAV1 can be found in Appendix B. The program is based on a method developed by Talwani and others (1959), who incorporated a line integral technique formulated by Hubbert (1948). Hubbert (1948) showed that the gravity effect of a polygonal mass in section is equal to the line integral around its perimeter. Essentially the program calculates the vertical component of gravitational attraction (the quantity measured in gravity surveys) across a two-dimensional polygon of infinite strike length, which approximates the configuration of the geologic mass being considered. By a process of trial and error, the shape of the polygon
is altered until a "best fit" is obtained between the calculated values and those residual (regional trend removed) values actually observed from fieldwork.

A body of infinite strike length is unrealistic for the case at Skalkaho. Also, there is no unique solution for the modeling of potential field (e.g. gravity, magnetics, and electromagnetics) data for a buried body (Telford et al, 1976). The possibilities can be narrowed because I have geologic field data in hand (e.g. delineated surface contacts and rock densities), and I know what one might expect to be a geologically reasonable solution. The fact that the modeling profiles are sub-parallel and perpendicular to the longitudinal trend of the pyroxenite optimizes the analysis. Also, the higher gravity values are centered over the higher density pyroxenites, which is what one might expect, and there is essentially no correlation between topography and the gravity anomalies in general, as shown in Figure 6.

The gravity data can be checked by a technique based on Gauss' Divergence Theorem. The theorem states that the integral of the divergence of a vector field over a region of space is equivalent to the integral of the outward normal component of the field over the surface enclosing the region. By applying the theorem to the gravitational field, mathematically, we have, \[ \int \nabla \cdot \vec{g} \, dv = \int \vec{g} \cdot d\vec{S} = \text{Total Mass} \] (Telford et al, 1976). Although, as previously noted, a given set of gravity values can be explained by a variety of mass distributions, it can be proved that the total anomalous mass in every such distribution is always the same and, what is more, the mass can be determined from the observed
FIGURE 6: PLOT OF ELEVATION VERSUS BOUGUER ANOMALY

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gravity data alone. In this case, the total calculated mass of the pyroxenite body is equal to the sum of the products of the residual Bouguer gravity values and the areas with those values (areas between the residual gravity contours enveloping the pyroxenite) (Parasnis, 1975). Since, the mass based of the model configuration (mass = volume times measured density) can also be determined and compared with the calculated anomalous mass, a check of the two theoretically-equal quantities can be made. For the Skalkaho pyroxenite, the anomalous mass is 2.0 billion metric tons, while the model mass is 2.4 billion tons. The two quantities are within 20 percent of each other. Some inconsistency is evident, but the two values are fairly close and well within an order of magnitude of variation. This tells me that my field results are at least workable. Therefore, I was able to accomplish my goal within the bounds of error to obtain a general, yet realistic impression of the shape of the Skalkaho Complex.

The modeling profile lines are shown on the Bouguer anomaly map (Figure 4). Gravity values range from -169 to -185 milligals. The most prominent anomalies are centered along profiles A-A' and B-B'. As revealed by the Bouguer anomaly map, a flat, -179 milligal regional "trough" rings the pyroxenite. This is consistent with Hassemer's (1984) small-scale survey covering the area, which shows that the complex is enclosed by -180 milligal contours (see inset, Figure 4). With this reasonable regional trend around the pyroxenite removed graphically (Telford et al, 1976), maximum residual gravity anomaly values along the profiles range from +2.5 to +8.5 milligals. Figures 7,
8, and 9 show these residuals and the results of the forward modeling process. Figure 10 is an isometric composite of the modeling results for the pyroxenite core with respect to the surrounding syenites.

The pyroxenite thins from east to west, with sections ranging from 1000 to 200 meters in depth, respectively. The gravity anomaly over the topographically-low, western end of the pyroxenite is relatively low and fairly flat. Even though station density is above average there, no computer modeling solution was possible with the data I have on hand and none may be possible anyway. I can only assume the pyroxenite distribution there is very irregular and thin. Still, this supports my contention that the pyroxenite there thins-out considerably, as do all the pyroxenite margins.

In the "saddle" between the two anomalous highs (at profiles A-A' and B-B') on the eastern end, two gravity stations have values of about -178 milligals that are not obvious due to the contour interval. This translates into a 1.0 milligal anomaly when the -179 milligal regional trend is removed. In comparison, the 2.5 milligal anomaly along profile D-D' (where the pyroxenite exposure is narrower than that across the "saddle") yielded a model section with an approximate depth to 200 meters. Therefore by inference, the 1.0 milligal anomaly across the "saddle" is indicative of a zone of pyroxenite thinning to less than 200 meters. Since the syenite is only exposed along the pyroxenite margin and as granodiorite exposures are nowhere near, I interpret the above to mean that there must be a near surface block of host rock beneath the "saddle", which was caught-up in or obstructed the pyroxenite during
FIGURE 7: MODEL ALONG PROFILE A-A'

Density = 2.63 g/cm³

Density = 3.26 g/cm³

Vert. & Horiz. Scale: 1" = 200 meters

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FIGURE 9: MODELS ALONG PROFILES C-C' AND D-D'

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Vert. & Horiz. Scales:
1" = 1400' (or 850 m. approx.)

FIGURE 10:
COMPOSITE ISOMETRIC MODEL
FOR PYROXENITE CORE WITH
SURROUNDING SYENITE
EXPOSURE
intrusion. This does not preclude the possibility that the above "block" could be carbonate rock, which if mostly calcite would have about the same density as the syenites, granodiorites and host rocks.

Some Notes on Magnetics

I originally intended to also use magnetic survey data to model the shape of the pyroxenite body in order to complement the gravity results, but irregular distribution of magnetite within the complex complicated this. At Rainy Creek, Boettcher (1967) noticed that magnetite-rich zones seemed to surround micaeous zones due to a differentiation process that was not structurally-controlled. There is some evidence of this at Skalkaho, but nothing conclusive.

Magnetic susceptibility is the significant variable in magnetics, playing the same role as density in gravity interpretation. Measurements taken from a dozen samples with a Bison model 3101 magnetic susceptibility meter are tabulated in Table 2.

The mica pyroxenites ranged from 0.000023 to 0.0051 cgs units, whereas amphibole pyroxenite readings varied from 0.00022 to 0.0021. Anhydrous pyroxenite values were low, with a typical susceptibility of 0.00026. The syenites ranged from 0.00016 to 0.00104. The wide range of magnetic susceptibilities reflect the irregular distribution of magnetite among the irregularly-distributed Skalkaho rock units. According to Lindsley (1966), a magnetic susceptibility of 0.00001 corresponds to a volume percent of magnetite (and/or other ferromagnetic minerals) of less than 0.01 percent. Susceptibilities of 0.0001 and
TABLE 2: MAGNETIC SUSCEPTIBILITY

<table>
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<tr>
<th>Rock Type</th>
<th>Number of Samples</th>
<th>Magnetic Susceptibility in cgs units</th>
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</thead>
<tbody>
<tr>
<td>Mica pyroxenite</td>
<td>3</td>
<td>0.000023 -- 0.00031 -- 0.0051</td>
</tr>
<tr>
<td>Amphibole pyroxenite</td>
<td>3</td>
<td>0.00022 -- 0.00032 -- 0.0021</td>
</tr>
<tr>
<td>Anhydrous pyroxenite</td>
<td>3</td>
<td>0.00020 -- 0.00026 -- 0.00029</td>
</tr>
<tr>
<td>Syenites</td>
<td>3</td>
<td>0.00016 -- 0.00051 -- 0.00104</td>
</tr>
</tbody>
</table>

0.001 correspond to volume percents of 0.1 and 1.0, respectively. So within the Skalkaho Complex, volume percents of magnetite range from approximately 0.01 to 3.0.

A set of rock property parameters within a reasonable amount of variation is required for each geologic body or bodies to be contrasted during modeling. A certain amount of averaging is always necessary, but the use of the mean of values that vary in orders of magnitude is unreasonable and would only produce ambiguous results (Serpa and Cook, 1984).

High frequency variations like the above are also detectable in the field with measurements from a magnetometer, since the intensity of magnetization so measured is directly proportional to magnetic susceptibility (Telford et al, 1976). My reconnaissance surveys over the pyroxenites at Skalkaho taken with a Bison model G816 proton magnetometer revealed that gradients of several thousand gammas per 30
meters were common. Boettcher's (1967) survey at Rainy Creek shows the same. The total field intensity of magnetization data for the area collected while the geologic mapping was done is contoured on my magnetic map (Figure 11). The lowest and highest magnetic intensities are 55406 and 66932 gammas, respectively. These two extreme readings were taken over the pyroxenite body. Figure 12 shows the magnetic survey stations with corresponding magnetic intensity values.
INTERPRETATIVE SUMMARY

My conceptual model for the Skalkaho pyroxenite-syenite complex in longitudinal section at the time of emplacement is shown in Figure 13. The probably immiscible magma was shallowly-emplaced to form a narrow, inward-dipping cone, and not a sill or outward-dipping cone. The pyroxenite body was split by a rib of host rock above the vent, but portions of the pyroxenite are still at least 1000 meters thick. Yet, the base of the complex proper is too shallow to have been truncated by the detachment zone beneath it. In the Skalkaho model, I have assumed that the mica, amphibole and anhydrous pyroxenites entirely comprise the mafic unit. However, this does not preclude the possibility that high density mafic rocks associated with other mafic-alkaline complexes, such as ijolite (nepheline-augite rock) and/or jacupirangite (magnetite pyroxenite) could exist at the base of the complex (Hyndman, 1985; p. 360).

Based on the lowest and highest exposures, the syenite occupies the flank of the pyroxenite and in places extends to as much depth as the pyroxenite. This does not preclude the possibility that some syenite may have capped the pyroxenite before erosion. I have assumed that the syenite body is sub-parallel to the sides of the pyroxenite and that the outer flanks of the syenite do not dip away from the complex, but in fact they may be outward-dipping. Also, it is reasonable to think that the complex roof-host rock contact was nearly horizontal at the time of emplacement. Though of different magma source, the contemporaneous, more or less identical Rainy Creek Complex formed a wider body, since
FIGURE 13:
CONCEPTUAL MODEL FOR
SKALKHO IGNEOUS COMPLEX
(in longitudinal section)

HOST ROCKS

PYROXENITES

SYENITES

HOST ROCKS

SYENITES

Approx. Vertical & Horizontal Scales:
1" = 600 m.
the exposures there are more circular (Boettcher, 1967).

In a regional sense, the mid-Cretaceous Skalkaho and Rainy Creek intrusions are not carbonatite complexes. Genuine Cordilleran carbonatite complexes, such as those at Gem Park, Colorado (Parker and Sharp, 1970), Iron Hill, Colorado (Nash, 1972), and Ice River, British Columbia (Currie, 1976) differ substantially from the intrusions in western Montana. The other complexes abound in volumes of nepheline syenite and petrogenetically-related carbonate rock, and are much larger than the Montana intrusions.

In the interest of a broader petrologic overview, the Skalkaho Complex (Lelek, 1979) and the "classic" carbonatite complex at Magnet Cove, Arkansas (Erikson and Blade, 1963) are compared as follows. The Magnet Cove Complex is pre-Mississippian in age (some 330 million years old) and was intruded into Paleozoic (Ordovician to Mississippian) sedimentary rocks, probably near a rifted margin. The Skalkaho Complex, on the other hand, was hosted by a mid-Proterozoic metasedimentary rocks during the mid-Cretaceous, inboard of an active converging margin. Deformation of host rocks due to intrusion was slight in both areas. The complex in Arkansas is thirty percent larger, covering an area of 13 sq. km. Magnet Cove is described as a ring dike complex, whose rocks intruded during separate but closely related periods. The pyroxenite and syenite at Skalkaho took the shape of a narrow, inward-dipping cone and were contemporaneously emplaced as a co-magmatic, probably immiscible system. The Magnet Cove Complex has a core of ijolite and carbonatite, an intermediate ring of trachyte and phonolite, an outer
ring of nepheline syenite and two masses of jacupirangite. Smaller
dikes of pegmatite and aplite are widespread. Similarly, the Skalkaho
Complex has a core of pyroxenite with alkali syenite-syenite bodies
along the pyroxenite flanks at depth, and is probably a "ring" complex
also. But, there is a noted lack of nepheline syenite. Also, there are
only two, small trachyte bodies and one small, pegmatite exposure at
Skalkaho.

Hyndman (1985; p. 353) suggests that mafic-alkaline complexes
such as those at Skalkaho and Rainy Creek evolved in areas over the
deeper parts of ocean-continent subduction zones behind the main arc
chain and in the later stages of its formation. Beyond this conjecture,
however, the tectonic significance of the Skalkaho Complex remains
inexplicable.
REFERENCES


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APPENDIX A:

REDUCED GRAVITY DATA
<table>
<thead>
<tr>
<th>STATION</th>
<th>LATITUDE</th>
<th>LONGITUDE</th>
<th>ELEVATION</th>
<th>UNBENDING PRECISELY</th>
<th>CORRECTION 3</th>
<th>ANOMALIES</th>
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</thead>
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<tr>
<td>111111</td>
<td>-90.57</td>
<td>-115.51</td>
<td>5460.0</td>
<td>90028.99 900731.35</td>
<td>7.96 11.19</td>
<td>200.55 151.99 91.59 127.26 182.57</td>
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<td>-115.51</td>
<td>5460.0</td>
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<td>5.53 12.16</td>
<td>100.46 144.86 88.18 109.45 135.05</td>
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<td>200.55 151.99 91.59 127.26 182.57</td>
</tr>
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<td>-115.51</td>
<td>5460.0</td>
<td>90028.99 900731.35</td>
<td>2.06 5.31</td>
<td>245.56 1.51    63.52 175.78 140.26</td>
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<td>2.06 5.31</td>
<td>245.56 1.51    63.52 175.78 140.26</td>
</tr>
</tbody>
</table>
APPENDIX B:

GRAVITY MODELING PROGRAM 'GRAV1'
**Program Grav1**

*Modified from GRAV, by MC Stickney during April, 1980.*

**Input File IN, DAT Contains:**

- **Line 1:**
  - Number of points at which gravity will be computed, distance between points (meters), # of sides of the polygon and the density contrast between polygon and surrounding material (grams/cc).
- **Line 2:**
  - Through # of polygon sides (2F).
- **Line 3:**
  - Depth in meters and distance from left side of profile.
- **Line 4:**
  - Enter Z, X points from left to right.
- **Line 5:**
  - One pair per line.
- **Following lines contain:** (F)
  - The observed gravity anomaly at each point where gravity will be computed, one value per line.

***Example***

<table>
<thead>
<tr>
<th>Points</th>
<th>Anomaly (mGal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>10</td>
</tr>
<tr>
<td>1000</td>
<td>0.5</td>
</tr>
<tr>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>1000</td>
<td>2000</td>
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<tr>
<td>1000</td>
<td>3000</td>
</tr>
<tr>
<td>1000</td>
<td>4000</td>
</tr>
<tr>
<td>1000</td>
<td>5000</td>
</tr>
</tbody>
</table>

**Example of COBOL Program**

```cobol
00010C... PROGRAM GRAV1.
00020C... MODIFIED FROM GRAV, BY MC STICKNEY DURING APRIL, 1980.
00030C... INPUT FILE IN, DAT CONTAINS (4F):
00040C LINE 1:
00050C# OF POINTS AT WHICH GRAVITY WILL BE COMPUTED, DISTANCE
00060CBETWEEN POINTS(METERS), # OF SIDES OF THE POLYGON AND
00070CTHE DENSITY CONTRAST BETWEEN POLYGON AND SURROUNDING
00080CMATERIAL(GRAMS/CC).
00090C LINE 2 THROUGH # OF POLYGON SIDES (2F):
00100C DEPTH IN METERS AND DISTANCE FROM LEFT SIDE OF PROFILE
00110C ENTER Z,X POINTS FROM LEFT TO RIGHT,
00120C ONE PAIR PER LINE.
00130C FOLLOWING LINES CONTAIN (F):
00140C THE OBSERVED GRAVITY ANOMALY AT EACH POINT WHERE
00150C GRAVITY WILL BE COMPUTED, ONE VALUE PER LINE.
00160
00170C***EXAMPLE***
00180C 1000 10 -0.5
00190C 2000 2000
00200C 3000 3000
00210C 4000 4000
00220C 5000 5000
00230C 0.1
00240C 0.5
00250C 1.4
00260C 2.6
00270C 3.1
00280C 4.2
00290C 2.7
00300C 1.6
00310C 0.8
00320C 0.0
00330C 0.0
00340C
00350C***************
00360
00370 DIMENSION XX(300), X(51), Z(51), GSUM(300), XA(51), ZA(51)
00380 DIMENSION POLY(51), RES(51), GO(51)
00390 TAN(X)=SIN(X)/COS(X)
00400 PI=3.1415927
00410 OPEN (UNIT=5, DEVICE='DSK', ACCESS='SEQIN', FILE='IN, DAT')
00420 READ(5,1000) KKK, CO, N, DENS
00430 FORMAT(2(I,F))
00440 NPOL=1
00450 EPS=.0001
00460 CDENS=-DENS
00470 DO 1040 J=1,N
00480 READ(5,1050) Z(J), X(J)
00490 IF(Z(J),EQ,0.0) Z(J)=Z(J)+EPS
00500 FORMAT(2F)
00510 CONTINUE
```

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DO 1008 I = 1, KKK
READ(5, 1010) GO(I)
FORMAT(F)
CONTINUE
ZERO THE POLY ARRAY
DO 925 I = 1, KKK
POLY(I) = 0.
GEE = 6.67E-3
CONTINUE
DO 650 NC0 = 1, NPOL
COMPUTATIONS FOR NPOL TIMES
END
DO 20 I = 1, N
XA(I) = X(I)
ZA(I) = Z(I)
CONTINUE
X(N + 1) = X(1)
Z(N + 1) = Z(1)
DIST = -C0
ZERO THE GRAVITY ARRAY
DO 920 I = 1, KKK
GSUM(I) = 0.
DO 600 K = 1, KKK
DIST = DIST + C0
XX(K) = DIST
FORMAT(//)
DO 500 I = 1, N
J = I + 1
A = X(I)
B = X(J)
C = Z(I)
D = Z(J)
GO TO 49
GZ = 0.0
PHI = 0.0
GO TO 499
THE FOLLOWING LOGIC TESTS FOR SPECIAL CASES
IF(A) 71, 51, 71
IF(C) 52, 50, 52
IF(R) 53, 50, 53
IF(C - D) 110, 130, 110
IF(R) 72, 81, 72
IF(C - D) 72, ATAN(C/A)
THETA1 = ATAN(C/R)
THETA2 = ATAN(R/B)
IF(THETA1 - THETA2) 73, 50, 73
IF(A - B) 74, 140, 74
IF(C - D) 160, 130, 160
IF(C - D) 82, 130, 82
IF(B - R) 120, 50, 120
SPECIAL CASES

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COMPUTATION FOR CASE ONE

01010C 010 CALL APACHEC(A,B,C,D,PHI)
01020 110 CALL ATERM(A,B,C,D,PHI,AA)
01030 CALL A2CHEK(B,D,T2)
01040 ALPHA=T2-PI/2.0
01050 TPHI=((D-C)/(B-A))
01060 BETA=TPHI*ALOG(COS(T2)*(TAN(T2)-TPHI))
01070 GZ=AA*(ALPHA+BETA)*(-1.0)
01080 490 GZ=AA*(ALPHA+BETA)*(-1,0)
01090 GO TO 499

COMPUTATION FOR CASE TWO

01010C 010 CALL APACHEC(A,B,C,D,PHI)
01100 120 CALL ATERM(A,B,C,D,PHI,AA)
01110 CALL A1CHEC(A,C,T1)
01120 ALFA=T1-PI/2.0
01130 TPHI=((D-C)/(B-A))
01140 BETA=TPHI*ALOG(COS(T1)*(TAN(T1)-TPHI))
01150 GZ=AA*(ALPHA+BETA)
01160 GO TO 499

COMPUTATION FOR CASE THREE

01010C 010 CALL APACHEC(A,B,C,D,PHI)
01200 130 IF(A>131,132,131
01210 131 IF(B)134,133,134
01220 132 T1=PI/2.0
01230 CALL A2CHEK(B,D,T2)
01240 GO TO 135
01250 133 T2=PI/2.0
01260 CALL A1CHEC(A,C,T1)
01270 GO TO 135
01280 134 CALL A1CHEC(A,C,T1)
01290 CALL A2CHEK(B,D,T2)
01300 135 GZ=C*(T2-T1)
01310 PHI=0.0
01320 GO TO 499

COMPUTATION FOR CASE FOUR

01010C 010 CALL APACHEC(A,B,C,D,PHI)
01330 140 CALL A1CHEC(A,C,T1)
01340 141 CALL ATERM(A,B,C,D,PHI,AA)
01350 CALL A2CHEK(B,D,T2)
01360 GZ=A*ALOG(ABS((COS(T1))/(COS(T2))))
01370 PHI=0.0
01380 GO TO 499

COMPUTATION FOR THE GENERAL CASE

01400 160 CALL APACHEC(A,B,C,D,PHI)
01410 CALL ATERM(A,B,C,D,PHI,AA)
01420 CALL A1CHEC(A,C,T1)
01430 CALL A2CHEK(B,D,T2)
01440 ALPHAT1-T2
01450 TPHI=((D-C)/(B-A))
01460 R1=COS(T1)*(TAN(T1)-TPHI)
01470 R2=COS(T2)*(TAN(T2)-TPHI)
01480 1111R=R1/R2
01490 BETA=TPHI*ALOG(R)
01500 GZ=AA*(ALPHA+BETA)
01510 499 GSUM(K)=GZ*2.0*DENS*GEE+GSUM(K)

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DO 10 I=1,NN
X(I)=X(I)-C0
10 CONTINUE

FOR HORIZONTAL DISTANCE OUTPUT IN METERS,
600 CONTINUE
12 K=1,KKK
XX(K)=XX(K)/1000.0
12 CONTINUE

RETURN
END

SUBROUTINE ATERM (AX, BX, CX, DX, P2, AA)
A1=BX+(DX*{(BX-AX)/(CX-DX)})
AA=A1*SIN(P2)*COS(P2)
RETURN
END

SUBROUTINE AlCHEC (XA, XC, T1)
PI=3.1415927
IF (XC/XA) 2,4,4
T1=ATAN(XC/XA)+PI
GO TO 11
4 T1=ATAN(XC/XA)
11 CONTINUE
RETURN
END

SUBROUTINE A2CHEK (XB, XD, T2)
PI=3.1415927
IF (XD/XB) 5,6,6
T2=ATAN(XD/XB)+PI
GO TO 11
6 T2=ATAN(XD/XB)
11 CONTINUE
RETURN
END

SUBROUTINE AHCHEC (XA, XB, XC, XD, PHI)
PI=3.1415927
IF ((XD-XC)/(XB-XA)) 7,8,8
PHI=ATAN((XD-XC)/(XB-XA))+PI
GO TO 11
8 PHI=ATAN((XD-XC)/(XB-XA))
11 CONTINUE
RETURN
END