Crustal structure of northwestern Montana

David Wm. Harris

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CRUSTAL STRUCTURE OF NORTHWESTERN MONTANA

by

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Chairman, Board of Examiners

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Date
Northwestern Montana is a structurally complex and diverse region of the northern Rocky Mountains. The regional Bouguer gravity map of the area demonstrates significant differences in the crustal structure between northwestern Montana and surrounding areas.

Gravity modeling of the long-wavelength Bouguer anomaly, which is believed to be related to the configuration of the crust-mantle boundary, agrees well with previous seismic refraction surveys indicating a crustal root under the approximate position of the Rocky Mountain Trench. The Purcell anticlinorium and related geophysical anomalies north of the Lewis and Clark line and south of the Moyie fault appear to be the result of high-density low-susceptibility Purcell sills emplaced into the Lower Prichard approximately 870 m.y.b.p. Subsequent to their emplacement the sills were deformed concentrically with the encasing Belt strata by compressional forces related to the formation of the fold and thrust belt. Later modification by extensional tectonics and erosion led to the present day configuration of the Purcell anticlinorium and related features such as the Sylvanite anticline. A combination Purcell sill-basement ramp anticline model is also possible and, therefore, does not preclude the possibility of crystalline basement involvement in thrusting at depth.

It appears unlikely that Phanerozoic rocks extend west of the Whitefish listric normal fault in the subsurface, therefore exploration for Paleozoic hydrocarbon reservoirs should be limited to the area immediately west of Glacier National Park. Additionally, the probability of Paleozoic strata in the subsurface below the Hefty thrust decreases to the west toward the Rocky Mountain Trench. Two Tertiary basins of northwestern Montana, the Rocky Mountain Trench and the Kishenehn Basin, may be hydrocarbon productive if stratigraphic and structural development prove favorable.
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Table 1. Purcell sill/Prichard Fm. rock density vs. Purcell sill/Prichard Fm. rock percentage.......................... 29
Northwestern Montana is a structurally complex and diverse region in the western Cordillera of North America. The regional Bouguer gravity map of northwestern Montana, southern British Columbia and Alberta (Figs. 1 and 2; Plates 1-3) reveals significant differences in this region in contrast to surrounding areas. The region is dominated by the northwest trending gravity high of the Purcell anticlinorium which, in turn, is bounded by parallel lows both to the northeast and southwest (Plate 1). On the northeast the Purcell high is bounded by the low of the Rocky Mountain Trench and farther to the northeast the low of the Kishenehn Basin. To the west the bounding gravity low corresponds to the Libby Trough. The gravity high of the Purcell anticlinorium ends abruptly to the south at the Lewis and Clark line and to the north at the Moyie fault (Fig. 2; Plate 3). To the east the northwest striking gravity anomaly trends grade into the generally northeast striking anomalies reflecting the Archean crystalline basement structure of the Great Plains. West of the Purcell anticlinorium the northeast trends give way to amoeboid anomalies of the Idaho Batholith area and Eastern Metamorphic Belt (Fig. 1).

The obvious differences pointed out above in the gravity signature of northwestern Montana, southern British Columbia and Alberta, as opposed to surrounding areas, suggest a differing crustal structure.
The primary purpose of this study is to combine existing geologic and geophysical data with new gravity data generated as part of this study to give a comprehensive picture of the crustal structure of northwestern Montana with particular emphasis on the structure and evolution of the Purcell anticlinorium. I focus on the area roughly defined by the Kalispell and west half of the Cut Bank U.S.G.S. 1 by 2 degree topographic sheets.
CHAPTER II

PURCELL ANTICLINORIUM: PROGRESS AND PROBLEMS

Structural development of the Purcell anticlinorium has been discussed in a number of investigations since 1977 (Wynn et al., 1977; Harrison et al., 1980; Constenius, 1980; Price, 1981; Fountain and McDonough, 1984). Any interpretation as to the structural development of the Purcell anticlinorium (south of 49 degrees N) must take into consideration the prominent gravity high as well as the lack of any corresponding magnetic anomaly over the feature. Wynn et al. (1977), utilizing audio-frequency magnetotellurics and gravity, modeled the anticlinorium as a horst block rising 11 km. above a flat crystalline basement at a depth of 17 km. The pre-Belt crystalline basement horst complex suggested by Wynn et al. (1977) is 25 km. across and 6 km. below the surface. Wynn et al. dismissed the aeromagnetic data because it showed only local highs over magnetite-rich Ravalli Group rocks. Thus the magnetic anomalies do not correlate with deeper structure. Harrison et al. (1980) concur and note that, "the deeply buried Precambrian crystalline rocks show no recognizable magnetic expression". Harrison et al. (1980) interpreted the Precambrian crystalline rocks of northwestern Montana to be part of the magnetically quiet basement observed to the south in the Great Basin.

Harrison et al. (1980) suggest stacked slices of crystalline basement involved in thrusting west of the Rocky Mountain Trench are the cause of the gravity anomaly and, in their model, put the basement 6 km.
below the surface to explain the lack of a magnetic expression. Gravity modeling by Constenius (1981) essentially concurs with the efforts of Harrison et al. (1980). Both studies require that faults such as the Whitefish (Wigwam), Lewis, Pinkham, Hefty and Libby all be major thrusts whereas geologic evidence (e.g. Johns, 1970; Harrison, 1983) suggest that some of these may indeed have minor stratigraphic offset.

Price (1981), working in the southern Canadian Rockies, proposed that northwest of the St. Mary and Moyie faults (Fig. 1) the Purcell anticlinorium is, "a geometric consequence of the juxtaposition of the thick northeasterly tapering prism of sediment that had accumulated above the zone of abrupt crustal attenuation, outboard from the continental margin, with relatively flat, planar basement surface on the continental platform". Price (1981), in the same vein as Bally et al. (1966), does not favor crystalline basement rock involvement in the development of the Purcell anticlinorium northwest of the St. Mary and Moyie faults but does recognize the possibility of a different style to the south as postulated by Wynn et al. (1977). Price (1981) also points out that suspected basement rocks occur above the Purcell thrust fault at about 52 degrees 30 minutes.

Fountain and McDonough (1984) favor a ramp anticline model for the evolution of the Purcell anticlinorium and use dense crystalline basement (2.87 gm/cc) at the core of the anticline 5-10 km. below the surface to account for the observed gravity. Fountain and McDonough theorize that the Lewis thrust transported the crystalline basement to its current position. A problem arises, however, in trying to envision
dense 2.87 gm/cc material thrust up from their postulated 2.75 gm/cc crystalline basement.
Gravity data collection

During the summer and fall of 1981 I measured the acceleration of gravity, using a Worden gravimeter, at 389 stations in northwestern Montana and northern Idaho. Readings were taken at road intersections, bench marks, or any other place where an elevation could be found on a U.S.G.S. 7 1/2 minute topographic map. The survey extends west from Cut Bank, Montana to Sandpoint, Idaho and from Kalispell, Montana north to the Canadian border.

The readings taken at the 389 stations included 15 base stations. Loops were made by taking a reading at one of the 15 base stations and within a three hour period (approximately) taking readings at as many stations as possible and then returning to the base station in order to "tie the loop". The vast area covered by the survey did not allow for tying all base stations in one loop, therefore, as the distance about the loop became difficult to travel in three hours other base stations were set up to allow for expansion of the survey. In this manner traveling back and forth between base stations allowed for determination of the differences in the acceleration of gravity at the base stations. Readings taken at a base station every three hours allowed for determination of drift of the gravity survey each day and subsequent removal of such drift. Additionally, a reading taken at the Kalispell...
Airport, a location of known absolute gravity (with a value of 980,567.39 mgals), and tied into the rest of the survey in the manner described above allowed for the determination of the absolute gravity at all stations.

Gravity data reduction

United States Geological Survey computer programs were used to reduce gravity meter readings to observed gravity values by calculating and correcting for earth-tide and linear meter drift. The theoretical gravity value was calculated using the 1967 formula of the Geodetic Reference System (International Association of Geodesy, 1967) given below.

\[ G = 978031.85 \left(1 + 0.005278795 \sin^2 \text{LAT} + 0.000023462 \sin^4 \text{LAT}\right) \]

where LAT is the latitude of the station in degrees and G is the theoretical gravity in milligals.

Complete terrain corrections were also made by the U.S.G.S. Terrain corrections were made for each station out to a radius of 166.7 km. using the method of Plouff (1977). The terrain corrections computed by the U.S.G.S. are based on mean elevations digitized on a 15-second grid for 0 to 5 km., 1-minute terrain data for the corrections from 5 to 21 km., and 3-minute terrain data for the corrections from 21 to 166.7 km. Terrain corrections were calculated in two parts from 0 to .895 km. (through the F ring (Bible, 1962)) and from .895 to 166.7 km. The
near correction (from 0 to .895 km.) is often calculated by hand but due to the scope of this paper and the vast amount of time involved to make the inner correction by hand the near correction computed by the U.S.G.S. was used instead. Before using the U.S.G.S. near-terrain correction values the validity of the computer calculated near-terrain corrections were tested in several areas. Even in areas of high relief such as Glacier National Park near terrain corrections varied less than 2 milli­gals (and much less in areas with lower relief) from the computer corrected values used in this study. The two terrain values calculated were added together to obtain the total terrain correction. A density value of 2.67 g/cc was assumed in calculation of all terrain corrections. The U.S.G.S. computer program also incorporates earth curvature corrections into the complete (terrain corrected) Bouguer anomaly values. Complete Bouguer values were calculated for each station using an average rock density of 2.67 g/cc. Computed terrain corrections and Bouguer anomaly values are given in Appendix.
Many aspects of the crustal structure of northwestern Montana are controversial and, indeed, poorly understood. It is my attempt here to combine available gravity data, seismic reflection and refraction data and previous geologic studies into a structural model of northwestern Montana.

To arrive at a reasonable structural model for the northwestern Montana region surface geology from previous studies (principally Johns, 1970; Harrison, 1983; Ross, 1959), refraction seismic studies (Hales and Nation, 1973; Asada and Aldrich, 1966; Bennett et al., 1975; Chandra and Cumming, 1972; Cumming et al., 1978; Mereu et al., 1975; McCamy and Meyer, 1964; Hill, 1972; Steinhart and Meyer, 1961), previous gravity studies (Harrison et al., 1980; Wynn et al., 1977; Constenius, 1980, 1982; Kulik, 1982; Fountain and McDonough, 1984), a reflection seismic line east of the Purcell anticlinorium were combined with two-dimensional gravity modeling utilizing gravity data collected for this study combined with a larger data base consisting of U.S. Geological Survey sources (Wilson, 1978, 1979; McBride et al., 1980; Brickey et al., 1982; Kulik, 1982), University of Montana data (Stickney, 1980) and Defense Mapping Agency data. All gravity data mentioned above were entered into the University of Montana computer system and subsequently plotted at the same scale as the U.S.G.S. 1 by 2 degree topographic sheets. Gravity data for the Kalispell, Cut Bank,
and Wallace 1 by 2 degree sheets were then contoured by hand after elimination of spurious points (Plates 1-3).

The gravity data were modeled utilizing a two-dimensional program written in BASIC by Campbell (1983) of the U.S.G.S. and modified for an APPLE II+ utilizing Microsoft BASIC. The computer program used in modeling is a "Talwani-type" program (i.e. the program calculates potential-field anomalies over horizontal prismatic bodies having planar faces). The "Talwani-type" programs were first introduced by Heirtzler et al. (1962) and Talwani and Heirtzler (1964). The program used in the gravity modeling is "two dimensional", that is, the source body is taken to be infinitely long in the strike direction. Since the structures of northwestern Montana generally strike consistently to the northwest (Plate 1) the two-dimensional gravity modeling should work well. This is, unfortunately, not true in all areas and must be taken into consideration in gravity modeling. An example of this problem is the Rocky Mountain Trench. Although the Rocky Mountain Trench is physically continuous in the strike direction it does not everywhere have the same amount of low density fill. This is particularly evident in the vicinity of cross section A-A' where little fill is present relative to its continuation to the northwest and southeast. Low density fill to the northwest and to the southeast does influence the observed gravity along A-A'. Therefore, I modeled the influence of the body trench by including a schematic Rocky Mountain Trench body (see Plate 4). The density value assigned to the Rocky Mountain Trench body is not as negative as that of the Kishenehn Basin to the east (i.e. -.25 gm/cc contrast vs. -.35 gm/cc for the Kishenehn basin). The influence of the
trench fill is somewhat diminished because it does not directly underlie the gravity profile. In order to account for edge effects (i.e. the effect of bodies ending abruptly at the gravity model edge when in reality the bodies are generally continuous past the end of the profile) the gravity model was continued 60.97 km (200,000 feet) to the southwest and 91.46 km (350,000 feet) to the northeast past the zone of interest shown on A-A' (Plate 4). Topography used in modeling gravity profile A-A' was visually averaged in a predominately strike direction. The topography shown on A-A' (Plate 4) is the actual topography.

After choosing a suitable line of cross-section roughly perpendicular to regional strike (Plates 1 and 2) the next step in modeling the crustal structure of northwestern Montana was to construct a regional structure cross-section from surface geologic maps. Johns' (1970) geologic mapping in Lincoln and Flathead counties in northwestern Montana still stands as the only mapping that is complete from the North Fork of the Flathead River west to the Idaho border. I used Johns' map as my primary source for the cross-section west of the North Fork of the Flathead, integrating the more recent structural interpretations of Harrison et al. (1983) where necessary. For consistency, I used the stratigraphic nomenclature of Johns' (1970) for rocks west of Glacier National Park. In Glacier National Park itself and to the east I used the geologic mapping and stratigraphic nomenclature of Ross (1959). Since some of the Belt stratigraphic nomenclature has evolved since the publication of Johns' and Ross' works I have included a correlation chart (Fig. 3).
CORRELATION CHART OF BELT NOMENCLATURE ACCORDING TO SELECTED REFERENCES


BASE NOT EXPOSED

FIG. 3
The thickness of various formations was calculated directly from the geologic maps using the dips and contacts given combined with information in the text (Johns, 1970) concerning various measured sections their locality and thickness. The attitude of the crystalline basement east of Glacier National Park was taken from Mudge's (1982) basement map of the northern disturbed belt of Montana (Fig. 4). Structure on the Lewis thrust of Glacier National Park was taken from Gordy et al. (1977) (Fig. 5). Structure of the Paleozoic and Mesozoic sections under the Lewis thrust plate was modified by myself using gravity modeling after the work of Bally et al. (1966) and Kulik (1982) (Fig. 6). The structure cross-section A-A' (Plate 4) in the vicinity of the Kishenehn basin, on the west side of Glacier National Park (Plates 1 and 2), differs little on a broad scale from the detailed work of Constenius (1981, 1982) with the exception of my interpretation of the Hefty-Nyack fault relationship to be discussed later.

The gravity maps of the region are dominated by the gravity high of the Purcell anticlinorium which in turn is surrounded by parallel gravity lows. In looking at this Bouguer gravity pattern (Fig. 1; Plates 1 and 2) one must decide what regional gravity profile must be removed to isolate the more shallow, short-wavelength sources. The low-pass filtered Bouguer anomaly map (cutoff wavelength of 250 km.) of Hildenbrand et al. (1982) (Fig. 7) shows a particularly prominent Bouguer gravity low over northwestern Montana. In the study area the map shows a low of approximately -160 mgal. rising both east and west.
FIGURE 4 Structure map on Precambrian crystalline basement. FROM MUDGE, 1982

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FIGURE 6

FROM GORDY ET AL., 1977
To test whether Hildenbrand's map may indeed represent the configuration of the crust-mantle boundary I decided to two-dimensionally model the gravity response using depths taken from various seismic refraction studies. Work by Bennett et al. (1975) between latitudes 50 and 53 north along the Rocky Mountain Trench, in the area of a -200 mgal. gravity low (Fig. 2), indicates that the thickness of the crust is in excess of 50 km. Moreu et al. (1977) in a survey in the vicinity of Jasper, Alberta, in the high Canadian Rockies, also determined the thickness of the crust to be approximately 50 km. Cumming et al. (1978) at approximately 50 degrees north in southern Canada determined that the Moho dips east from approximately 30 km. near Highland Valley (at 50 degrees north latitude, -121 degrees east longitude) to greater than 40 km. under the Purcell anticlinorium. Chandra and Cumming (1972) determined that a crustal root of approximately 5 km. exists under the Rocky Mountains along latitude 50 degrees 30 minutes.

Workers in the United States have apparently found a similar crustal root under the Montana portion of the northern Rocky Mountains. Depth of the crust-mantle boundary would not be expected to be as great as that under the Canadian Rockies as suggested by the differing Bouguer anomaly values (Fig. 2). Work by McCamy and Meyer (1964) indicates the crust between Glacier National Park and the Rocky Mountain Trench may be as thick as 43 km. Asada and Aldrich (1966) working with the data of Steinhart and Meyer (1961) and McCamy and Meyer (1964) inferred that the Moho boundary dips west from the continental divide. Hill (1972), from refraction data in eastern Washington, determined that the crust thins...
to between 30 and 35 km. to the west and southwest. Work by Hales and Nation (1973), with refraction data, determined the crust to be about 37 km. thick in the vicinity of the British Columbia and Idaho-Montana borders.

In modeling the crustal root I used two density contrasts between lower crust and upper mantle. Models A and B (Fig. 8) assumed the lower crust was less dense by 0.3 and 0.37 gm/cc respectively. The 0.3 gm/cc contrast was the density difference assumed by Fountain and McDonough (1984) in a study of northwestern Montana. Cady (1980) used a greater crust/mantle contrast of 0.37 gm/cc determined from velocity-density relationships (after Bateman and Eaton, 1967), to model crustal structure in the Omineca crystalline belt of northeastern Washington and southeastern British Columbia. Results of the models (Fig. 8 A and B) give a maximum depth to the Moho of 43.5 and 40 km. below sea level respectively with the crust-mantle interface rising both east and west.

The good fit between observed and theoretical gravity (Fig. 8 A and B) lends credibility to the use of a bowl-shaped regional for northwestern Montana in subsequent gravity modeling. In the same fashion as Fountain and McDonough (1984), I view the long-wavelength Bouguer low (Hildenbrand et al., 1982) as representative of the regional Bouguer pattern which is hidden in the observed gravity profile. In order to model the shallow sources I have mathematically subtracted this bowl-shaped regional component (Plate 4). The result is the residual gravity profile used with structural cross-section A-A' (Plate 4). The use of a bowl-shaped regional differs from that of Harrison et al.
CRUSTAL ROOT MODEL A

Fig. 8A

LEGEND
O — Regional Bouguer Gravity
X — Theoretical Gravity
(-3) — Density Contrast Used in Gravity Model
Body Shape Used for Gravity Model

MODEL DATUM = 1.5 Km

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CRUSTAL ROOT MODEL B

Fig. 8B

LEGEND
- O - Regional Bouger Gravity
- X - Theoretical Gravity
( - 37 ) - Density Corrections Used in Gravity Model
- - Body Shape Used for Gravity Model

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who assumed a linear regional with a decrease in the field of 0.2 mgal/km to the west.

Several features are obvious in the residual gravity profile along A-A' (Plates 1 and 4). Most outstanding is the prominent gravity high corresponding to the Purcell anticlinorium with gravity lows paralleling it both east and west. The low to the west corresponds to the Libby Trough while that to the east corresponds to the Kishenehn Basin. The Rocky Mountain Trench manifests itself along the profile as a slight flattening of the residual from approximately 114 to 130 km. A more developed part of the Rocky Mountain Trench (manifested as a more pronounced gravity low) can be seen both southeast and northwest of gravity profile A-A' (Plate 1). A subtle residual gravity high at the west end of the profile corresponds to an anticline cored by Prichard Formation on the Libby thrust plate.

One of my primary considerations in gravity modeling was the determination of reasonable densities for the important geologic units: 1) Lower Prichard-Archean crystalline rocks, 2) Belt Supergroup (exclusive of the Lower Prichard), 3) Paleozoic rocks, 4) Mesozoic rocks and 5) Quaternary-Tertiary rocks.

Various publications use widely varying densities for each of the above rock units. Below is a summary of some recent publications and densities used in their gravity modeling.
Harrison et al. (1980)

Phanerozoic rocks - 2.64 to 2.68 g/cc.
Belt rocks - 2.7 to 2.75 g/cc.
Crystaline Basement - 2.8 g/cc.

Kulik (1982)

Tertiary undivided - 2.35 g/cc.
Mesozoic undivided - 2.51 g/cc.
Paleozoic undivided - 2.76 g/cc.
Belt undivided - 2.65 g/cc.
Precambrian basement - 2.67 g/cc.

Constenius (1981)

Quaternary - 1.8 to 2.0 g/cc.
Tertiary - 2.1 to 2.63 g/cc.
Proterozoic, Paleozoic and Mesozoic undivided - 2.7 g/cc.
Archean crystalline basement - 2.8 g/cc.

Fountain and McDonough (1984)

Deformed sedimentary rock above basement - 2.7 g/cc.
Crystalline basement - 2.75 g/cc.
Basement material in ramp anticline (causitive body for Purcell anticlinorium gravity high) - 2.87 g/cc.

The densities I used for gravity modeling were derived from formation density logs from two wells (Plate 5): Shell Canada Resources Limited - b-30-H Shell MacDonald, in southeastern British Columbia and Husky Oil Co. - #1 Gulf Mercier in Glacier Co. Montana. Other wells in the area were examined but most proved to be of poor quality in the zones of interest. The program used in the modeling uses density contrasts rather than absolute densities. The densities used in modeling are all relative to the density of the Belt Supergroup undivided. The average densities assumed are given below with the relative densities used in modeling given in parentheses (also see

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Tertiary and Quaternary undivided -
2.32 to 2.35 g/cc

Mesozoic undivided - 2.49 to 2.52 g/cc

Paleozoic undivided - 2.74 to 2.77 g/cc

Belt undivided (excluding L. Prichard) -
2.67-2.7 g/cc

Lower Prichard and Archean Basement (causitive body for the Purcell anticline high) - 2.8 to 2.83

One of the main tools used in the interpretation of the Purcell anticline high and, indeed a constraint on the whole structure section A-A', was a reflection seismic line across the Star Meadow anticline (Plates 1 and 4). Velocities obtained from the Shell MacDonald well, southeast British Columbia (Fig. 9) were used to determine depth and thickness of a prominent reflection package observed on the seismic line beginning at approximately 1.35 seconds (crest of the Star Meadow anticline). The reflection package is seen to dip both northeast and southwest to 1.8 and 1.9 seconds respectively. Thickness of the reflection package varies from roughly 1.25 to 1.5 seconds which corresponds to a thickness of from 3700 to 4600 meters. The seismic reflection package is shown schematically on cross-section A-A'. One notable feature of the reflection package is that it appears to be concentric with the surface geology (i.e. anticlines and synclines exposed at the surface can be seen in the reflection package directly below). This observation leads to two obvious possibilities as to the relationship between the Belt at the surface and the rocks of the reflection package: 1) the rocks of the reflection package were deformed concentrically with the overlying Belt units with no intervening major thrusts (i.e. both the Belt, which is seen to crop out at the surface, and the reflection package are on the same thrust sheet); 2) the rocks above the reflection package were thrust over the underlying reflection
package and subsequently both hanging wall and foot wall rocks were deformed concentrically (i.e. folding followed thrusting). The obvious implication of possibility number one is that the reflection package could not possibly be Paleozoic or younger sediments.

As working constraints for my gravity modeling I made several assumptions: 1) the top of the seismic reflection package corresponds to the top of the causitive body for the Purcell anticlinorium gravity high and related anomalies; 2) the top of the causitive body occurs at a roughly constant stratigraphic level below the top of the Prichard Formation across the profile and is, therefore, due to its stratigraphic level absent in the vicinity of Glacier National Park: 3) there is little lateral density variation in the density units designated above, i.e. Paleozoic undivided, Belt undivided etc.; 4) the rocks of the reflection package (hereafter designated Lower Prichard) in the vicinity of the reflection seismic line were deformed concentrically with the overlying Belt with no intervening major thrusts (i.e. possibility 1 mentioned in above paragraph).

An interesting observation can be made upon casual inspection of the complete Bouguer maps of the Kalispell and Wallace quadrangles (Plates 1 and 3). Each of these Bouguer maps shows the outcrop pattern of the Prichard Formation (designated Yp). The pattern of Prichard outcrop corresponds well with gravity highs (north of the Lewis and Clark line) as would be expected from assumptions 2 and 4 above. The Sylvanite anticline, in extreme northwestern Montana, is a particularly good example of this relationship (Plate 1).
Reasonable velocities obtained for Belt sediments are in the range of 4725 to 6000 meters/second (Constenius pers. comm., 1985; Bally et al., 1966) and a sonic log from the Shell MacDonald well which bottomed in the Ravalli Group (Fig. 9). The synthetic seismogram (Fig. 9) shows that, although the reflections in the Paleozoic sequence are more prominent than those in the Belt, reflections in the Belt do occur and would be expected on a normal reflection seismic section. Depths to the prominent reflection package discussed above, using the velocities cited above (relative to sea level), are: 1) southwest limb - -3950 to -4900 meters; 2) crest - -2530 to -3080 meters; 3) northeastern limb - -3720 to -4480 meters. The depths shown in the final gravity model fit well using the Belt velocities cited above. The velocity of the Belt rocks over the crest of the Star Meadow anticline are inferred to be higher than the velocity of the rocks over the southwest or northeast limb. An increase in velocity with depth can be seen on the sonic log of the Shell MacDonald well (Fig. 9) where the velocity of the Kintla Formation (Missoula Group) is notably lower than that of the deeper Grinnell Formation (Ravalli Group). An increase of velocity with depth is quite common and could easily explain the inferred higher velocity of the rocks over the crest of the Star Meadow anticline.

A potential problem with the gravity modeling is the sparcity of gravity data along various parts of the profile (A-A'). This problem is particularly evident in the Whitefish Range (see Plate 1) where a cubic spline routine was used to interpolate values. Another potential problem with the gravity model is the inevitable error in the gravity measurements itself (terrain correction, station elevation etc.) and subsequent interpolation of these gravity values. Despite these innate problems in the data
the final model A-A' (Plate 4) works very well within the assumptions (1-4) outlined above. The model shows only slight variations in the thickness of the Prichard Formation above the causitive body (Lower Prichard) which is to be expected if the Prichard thickens to the west.

As mentioned above the density contrast of the Lower Prichard unit (or causitive body of the Purcell anticlinorium gravity high) used in the gravity modeling is .13 (absolute density of 2.8 - 2.83 gm/cc) which in some respects seem high. It is, however, within the range of previous works mentioned above (2.8 to 2.87 gm/cc.). As dictated by my assumptions the density contrast must be rather large (i.e. .13 gm/cc), and the causitive body broad and close to the surface in order to account for the observed residual gravity field. Other workers have used lower contrasts which requires, in general, a narrower body with great relief (Harrison et al., 1980; Wynn et al., 1977; Constenius, 1981). Fountain and McDonough (1984) use a greater contrast (.17), with the causitive body narrower and at a greater depth.

The evolution of the Purcell anticlinorium has been the subject of various papers and the cause of the gravity high (with a corresponding lack of a significant magnetic expression; see Plate 4) is still a matter for speculation. Within the bounds of the basic observations thus presented, in addition to evidence presented below, two principal models were deemed reasonable for the evolution of the Purcell anticlinorium and related anomalies: 1) emplacement of high-density, low susceptibility (probably altered) Purcell sills, the majority of whose intrusion is generally at a more or less consistent stratigraphic level in the Prichard Formation, with
subsequent deformation concentric with the encasing Belt (some of these sills crop out on the Sylvanite anticline); 2) a ramp anticline model (e.g. Fountain and McDonough (1984)) with the causitive body closer to the surface; and 3) a combination of 1 and 2.

The following rock types potentially fit the high-density low susceptibility criteria outlined above: 1) carbonates/evaporites; 2) metamorphics; 3) intrusive igneous rocks. Given the right circumstances each of these categories could fulfill the requirements. The correct combination of events and, therefore, causitive rock bodies must be deduced from the available data which by no means leads to a unique solution.

The use of a carbonate/evaporite sequence causes no conflict with the lack of a magnetic signature and further a thick sequence of dolomites/anhydrites could potentially give the proper density contrast required. In looking at the seismic (i.e. the strong reflection sequence) it is obvious qualitatively that strong velocity/density contrasts exist throughout the sequence. In order to create the observed reflection sequence high density/velocity rocks must alternate with relatively lower density/velocity rocks. Although the density of the pure mineral dolomite is approximately 2.87 g/cm³ (Tröger, 1952) in nature dolomite (dolostone) is generally impure and a density of 2.8 g/cm³ or less is probably a more realistic figure. If dolomite is the high density/velocity rock observed it must alternate with rocks of a lower density/velocity which would lead to a lower average density than required to give the residual gravity anomaly observed (i.e. less than the 2.8 - 2.83 required by the modeling and related observations discussed above). If, however, anhydrite
(2.96 gm/cc; Tröger, 1952) is used as the high density/velocity rocks and dolomite plus other rocks are used as the lower density/velocity rocks this would potentially increase the average density enough to account for the residual gravity anomaly. However, it is unlikely that a thick sequence of carbonates and/or evaporites are present in the Lower Prichard.

Smithson (1971) measured rock densities for seven different metamorphic terrains. Mean densities measured ranged from 2.7 to 2.86 gm/cc. Most mean rock densities of metamorphic terrains, however, fell between 2.7 and 2.79 gm/cc. Under the proper circumstances high density metamorphics could be contrasted with other metamorphics (say 2.76 gm/cc) to give the proper reflection sequence as well as the high average density needed to satisfy the residual gravity anomaly. Susceptibilities of metamorphic rocks are quite variable (Dobrin, 1976) and could potentially be of high density and yet of low susceptibility.

Harrison et al. (1972) state that, "Sills of Precambrian gabbro to quartz diorite are abundant in the lower part of the Prichard Formation." The study by Harrison et al. (1972) covers the region of the Purcell Trench of northern Idaho. Harrison et al. (1972) state that there is no time or genetic connotation implied, between the Purcell sills and the Purcell lava. The Purcell sills vary dramatically in thickness ranging up to 900 meters (3,000 feet) and also vary along their strike. The age of the sills is uncertain but a "fresh" sample gave an age of approximately 870 m.y.b.p. which Harrison et al. (1972) consider to be a minimum age. Density of the sills averaged approximately 2.92 gm/cc (Fig. 10) and were deemed to be of sufficient mass to produce well defined gravity anomalies.
Density and susceptibility values of the Purcell sills fit well within the requirements set forth above. It is not difficult to imagine that the Purcell sills could alternate with the normal Prichard Formation within the reflection sequence to give the high average density required (i.e. 2.8 to 2.83 gm/cc) over the 4573 meter interval observed seismically as well as cause the reflection pattern observed. In the vicinity of the Fairview anticline (Plate 1 and 4) the top of the causitive body (as modeled) starts at approximately 610 meters below sea level and continues down to 10,670 meters. In this area the causitive body is thus about 10,000 meters thick. Below 10,670 meters I have assumed that there are no lateral density variations, therefore, all density variations causing the residual Bouguer gravity anomaly lie above this depth. Table 1 shows Purcell sill and Prichard Fm. density versus Purcell sill and Prichard Fm. percentage over any interval which gives the 2.8 gm/cc average density required by gravity modeling.

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Table 1 - Purcell sill/Prichard Fm. rock density vs. Purcell sill/Prichard Fm. rock percentage over a given interval to give average density of 2.8 gm/cc over that interval.

It is a matter of conjecture which of these values for the density of the Purcell sills and the Prichard Fm. is correct. In my modeling I
use 2.67 to 2.7 gm/cc for the Belt Supergroup which leads to a roughly 50/50 ratio of Purcell sill to Prichard Formation rocks given the average density of 2.92 gm/cc (Harrison et al., 1972) for the sills. If a higher value for the average density of the sills and/or the Prichard Formation is used then the percentage of sills drops accordingly.

A hypothetical model of the evolution of the Purcell anticlinorium is shown schematically in Fig. 11. Injection of the Purcell sills takes place during or just subsequent to deposition of the Upper Belt (based on the dates given by Harrison et al. (1972) (Fig. 11; a, b). The Purcell sills are subsequently deformed concentrically with the rest of the Belt leading to the development of the Purcell anticlinorium (Fig. 11; c-e). Deformation in southern Canada within the fold and thrust belt spans the interval from late Jurassic to Paleocene time (Price and Mountjoy, 1970). Modification by extension and erosion leads to the present configuration (Fig. 11 f). This model uses the Purcell sills as the causitive body for the gravity anomaly, however, substitution of a carbonate/evaporite sequence or a metamorphic complex (possibly utilizing dense metamorphosed Lower Prichard Formation) for the Purcell sills could also fit the data as it stands. I believe, however, that the data best fits the Purcell sill scenario. The combination of a ramp anticline model (possibly in the form of basement involvement at depth) as in Fountain and McDonough (1984) and the Purcell sill model set forth above would not violate the data.
SCHEMATIC CROSS SECTION OF BELT BASIN
THE PURCELL ANTICLINORIUM
AND RELATED FEATURES

BELT BASIN PRIOR TO EMMPlACEMENT OF PURCELL SILLS

FIGURE II

David Wm. Harris 11/84
EMPLACEMENT OF PURCELL SILLS

LEGEND

□ ZONE OF PURCELL SILLS

→ RELATIVE DISPLACEMENT

PA PURCELL ANTICLINORIUM

NO SCALE

INCIPIENT THRUSTING DEFORMS PURCELL SILLS CONCENTRICALLY WITH BELT AND PHANEROZOIC SEDIMENTS

FIGURE II

David Wm. Harris 11/84
COMPRESSION

THRUSTING PROPAGATES TO THE EAST

CONTINUED PROPAGATION OF THRUSTING TO THE EAST LEADS TO DEVELOPMENT OF PURCELL ANTICLINORIUM & OTHER STRUCTURAL FEATURES

FIGURE II

David Hm. Harris 11/84
COMPRESSONAL FEATURES MODIFIED BY EXTENSION & EROSION

FIGURE II

David Wm. Harris 11/84
Two models of the structure in the vicinity of the Purcell anticlinorium are presented in cross-sections A-A' and C-C' (Plates 4 and 7). Both of these structure cross-sections are reasonable given the gravity modeling and the surface geologic data. The main difference in the cross-sections is the angle of the Pinkham thrust leading to a differing attitude of crystalline basement. In cross-section A-A' the attitude of the Pinkham is quite steep thus raising the possibility that the Lewis (basal thrust) drops off steeply (to avoid the Pinkham thrust cutting downsection in the direction of transport) suggesting the possibility of crystalline basement involvement below the Purcell anticlinorium in this area.

An alternate interpretation in the same area (C-C'; Plate 7) shows the Pinkham thrust as much shallower (in places a bedding plane thrust) thus allowing the basement to remain at a relatively constant angle across the cross-section. This model suggests that any basement involvement would show up to the west where the Lewis thrust may potentially involve crystalline basement. Either of these models of structure in the vicinity of the Purcell anticlinorium is valid given the data used in this study.

Oil and gas possibilities in northwestern Montana

Another controversial subject involving the structure of northwestern Montana has been determining how far to the west Phanerozoic rocks extend in the subsurface. This question is critical to determining how far west potential oil bearing strata may exist. The data at my disposal on the
subject are not, unfortunately, conclusive. In the determination of how much Paleozoic/Mesozoic strata could potentially be under Belt rocks west of Glacier National Park it is critical to take into consideration the following: 1) the thickness of the Belt west of the park; 2) the attitude of the crystalline basement west of the park; 3) the structural positions and configurations of various major thrusts in this vicinity (e.g. Hefty, Whitefish (Wigwam), Lewis etc.).

In the construction of cross-sections A-A' and B-B' (Plates 4, 6) values for thickness of Belt and attitude of basement played a major role. Boberg (1984) notes that by combining the thickness of the Belt found in the Shell MacDonald well with drilled thicknesses from the Pacific-Atlantic Flathead well (Plate 5), in addition to a local measured section, a thickness approximately 4880 meters of Belt can be determined in the area just west of Waterton National Park, Canada. This thickness agrees well with the 5213 meters maximum Belt thickness determined by Whipple et al. (1984) for Glacier National Park. Dip of the basement west of Glacier National Park is difficult to determine. Bally et al. (1966) put the dip of the basement at approximately 2 degrees. It is not unreasonable to put a greater dip on the basement west of Glacier National Park. Kulik (1982) states that the Belt strata in Glacier National Park are preserved in a shallow structural depression in the crystalline basement suggesting the possibility that the attitude of the basement is not constant. It is not clear how this basement depression would manifest itself west of the park and, therefore, does not preclude the possibility that the basement west of the park dips more steeply than to the east. The depth to the Lewis
thrust on cross-section A-A' west of the park was determined by gravity modeling constrained by surface geology in addition to the thickness of Belt cited above. The dip of the basement on cross-section A-A' is modeled at approximately 5 degrees.

Bally et al. (1966) note that the "Cambrian event of the foothills can be traced to the east side of the Trench." This implies that, at least in the southern Canadian Rockies, the Lewis plate rides on a veneer of Cambrian strata until it ramps at the position of the Flathead fault where a duplex of Paleozoics is developed below the Lewis plate. By combining gravity modeling with the observation of Bally et al., 6400 meters of Belt strata may be present between the Lewis and the Hefty plates (Plate 4; see theoretical gravity values vs. residual gravity anomaly curve). By using the 4880 meter thickness of Boberg (1984) up to 1525 meters of Paleozoic strata may exist under the Hefty plate (Plate 4; see alternative model theoretical gravity vs. residual gravity anomaly curve). The curve fit without Paleozoics beneath the Hefty plate is obviously better than the fit with the Paleozoics. This observation does not preclude the existence of Paleozoic strata beneath the Hefty plate in this area for a variety of reasons, including: 1) the density of data points in the Whitefish Range is rather low and may not reflect the true Bouguer gravity anomaly in the area; 2) density values may vary from those used in modeling; 3) the high density "Lower Prichard" unit utilized west of the Whitefish fault (see Plate 4) may be imbricates of Paleozoic rocks thereby requiring the Hefty thrust to cut up section faster than on A-A' and thus the Hefty would be shallower than shown. This would imply that Paleozoic strata may extend as far
west as the Rocky Mountain Trench.; 4) the dip of the basement may be greater than shown, thus allowing for but not requiring, more Paleozoic strata under the Hefty thrust. The nature of the Hefty thrust in the vicinity of A-A' is a matter of speculation, for its trace is not exposed much farther south than the Cleft Rock Mountain area (see Plates 1, 5, and 6, NE Kalispell quadrangle). From its position on Cleft Rock Mountain, where Missoula Group rocks overlie Paleozoic carbonates (see B-B', Plate 6), the Hefty ramps laterally more than 300 meters to a structurally lower position not far to the southeast. Constenius (1981, 1982) mapped a down-to-the-east fault, known as the Nyack, in approximately the same position as the Hefty fault would project. Constenius views the Nyack as a rotated antithetic normal fault related to the evolution of the Flathead listric normal fault system. It is possible, however, that the Nyack is indeed the Hefty thrust whose leading edge is buried by Cenozoic sediments of the Kishenehn Basin. The latter hypothesis is used in the construction of cross-section A-A'.

Structure cross-section B-B' is close to where Boberg (1984) calculated 4880 meters of Belt strata. Consequently, this thickness of Belt is used between the Lewis thrust and the Hefty-Wedge Mountain thrust system and still allows for a substantial thickness of Paleozoic strata even with the shallow dip of the basement (3 degrees) used. Manipulation of the angle of the Hefty and the dip of the basement could easily allow for more Paleozoics under the Hefty and potentially extend them as far west as the Rocky Mountain Trench.

Extension of Phanerozoic rocks in the subsurface west of the Whitefish
fault is also a matter for speculation, however, balancing a cross-
section with Phanerozoics west of the Whitefish fault is problematic.
Additionally, if the rocks of the Star Meadow anticline reflection
package were deformed concentrically with the overlying belt, and have
no intervening major thrusts, Paleozoic rocks, if they exist west of the
Whitefish fault, must be below the reflection sequence (i.e. greater
than approximately 7620 meters subsea in this area) and a major thrust
plate with a corresponding Belt package (although probably somewhat
thinner) repeated below. This, I feel, is a highly unlikely occurrence.
Moulton (1984) cited the presence of Cambrian rocks in the Libby Trough
as evidence that Paleozoics extend in the subsurface west under the
Libby thrust. In order to gain more Paleozoic strata in the subsurface
to the west under the Libby thrust the Libby would cut downsection in
the direction of transport. Cambrian rocks in the Libby Trough more
likely represent the last remnants of Paleozoic strata in the area which
were caught in thrust splays preserved by subsequent rotation of the
strata by listric normal faults rotated into an underlying thrust, and
therefore would not be expected to extend far into the subsurface to the
west (see Plate 4).

The potential for substantial amounts of Paleozoic strata in the
subsurface is greatest in and near Glacier National Park. Potential for
commercial hydrocarbon accumulations is good east of the Kishenehn Basin
where imbricate stacks of Paleozoics are postulated to exist southeast
along strike of the Pacific-Atlantic Flathead well (see A-A' and B-B';
plus Plate 5) which encountered Paleozoic strata below the Lewis thrust
at 1340 meters. West of the Kishenehn basin (A-A' and B-B') potential
for imbricate stacks of Paleozoic strata also exists under the Heft plate. The strata in these imbricate stacks is presumably equivalent to that which produce prolific amounts of hydrocarbons at Waterton Field in Canada. It seems reasonable to assume that if the same source and reservoir characteristics exist in the Paleozoic strata of the imbricate stacks east and west of the Kishenehn Basin, then finding commercial hydrocarbon production is dependent on the determination of a favorable structural position with a seal and mature hydrocarbon source. West of the Whitefish fault there appears little chance for the existence of Paleozoic strata in the subsurface, and therefore, little chance for commercial hydrocarbon accumulations.

Aside from the Paleozoic potential cited above, potential also exists in two Tertiary basins of northwestern Montana: the Rocky Mountain Trench and the Kishenehn Basin (Plate 1). The source and reservoir rock potential of the Rocky Mountain Trench of the United States is virtually unknown. In the United States the Rocky Mountain Trench is apparently the result of extension leading to development of a linear northwest-southeast striking system of listric normal faults which developed by rotation into reactivated thrust surfaces (A-A'; Plate 4). The differential movement of the normal faults has led to variable basinal development along the Rocky Mountain Trench and, therefore, differential valley fill along strike. Stickney (1980) suggests approximately 825 meters of valley fill in the vicinity of Kalispell. Stickney's modeling was not, however, over the area with the lowest gravity indicating that this is not a maximum value for thickness of fill. Additionally, if the density value of 2.2 gm/cc for Cenozoic
rocks used in the study is too low then the Rocky Mountain Trench would be deeper. Even if source and reservoir rocks exist in the Trench it is problematic whether the sediments have ever been buried deep enough to generate significant quantities of hydrocarbons. In the United States the Kishenehn Basin is a more developed version of the Rocky Mountain Trench. The sediments of the Kishenehn Basin are reportedly up to 3660 meters thick (Constenius pers. comm., 1985) and dip generally to the northeast into the Flathead fault which bounds the basin on the northeast. Constenius (1981) notes that rocks of the Kishenehn Basin are well suited as potential reservoir rocks. Mammal fossils and radiometric dating indicate the age of the Kishenehn sediments is early to middle Oligocene (33.2 ±/− 1.5 m.y.). Oil shales classified as kerogenous calcilutites and associated sapropelic coals are exposed in the basin and attain a thickness of approximately 85 meters (280') (Constenius and Dyni, 1983). It is unknown, however, how much of this potential hydrocarbon source rock is buried in the subsurface. These oil shales and coals are at the pre-generation stage at the surface (Constenius and Dyni, 1983), however, it seems reasonable to speculate that these rocks could reach thermal maturity in the subsurface. Numerous oil and gas seeps have been discovered in the vicinity of the Kishenehn Basin (Boberg, 1984; and Constenius, 1981). It is not known whether the source of the hydrocarbons is the sediments of the Kishenehn Basin or Paleozoic/Mesozoic sediments under the Lewis plate (Constenius, 1981). A deterrent to hydrocarbon exploration in the basin is the fact that large portions of the Kishenehn lie in Glacier National Park. If, however, the continuity of reservoir rock, in addition to favorable juxtaposition of source, seal, and reservoir rock, allows for updip mi-
migration over long distances some of the highest hydrocarbon potential could fortuitously lie outside the park.

Although it seems reasonable to assume that both stratigraphic and structural traps may exist within the Kishenehn Basin, structural traps would initially be easier exploration targets since subsurface stratigraphic information is sparse. Using geophysical techniques such as seismology and gravity analysis, structural traps could be defined. Structural traps may exist in the form of rollover structures bounded by listric and antithetic normal faults of the Flathead fault system. These postulated listric and antithetic normal fault-bounded rollover structures would presumably be best developed (as well as source rock more mature) in the deeper parts of the Kishenehn Basin and, therefore, potential for commercial hydrocarbon accumulation appears greatest inside Glacier National Park. Similar rollover structures along the Whitefish listric and antithetic normal fault system and related systems may exist in the Rocky Mountain Trench and could be potential targets for hydrocarbon accumulations.
CONCLUSIONS

The synthesis of the data thus presented leads to many speculations regarding the nature of the crustal structure in the northwestern Montana region. From the data presented it is reasonable to conclude that the Purcell anticlinorium is cored by Prichard Formation strata that have been intruded by high-density low-susceptibility Purcell sills at a generally consistent stratigraphic level. Subsequent to their emplacement the sills were deformed concentrically with the encasing Belt sediments. Ultimately, these sills give rise to the observed gravity and magnetic signatures as well as to the present structural configuration of the Purcell anticlinorium and related features (e.g. Sylvanite anticline). A combination Purcell sill-basement ramp anticline model is not in violation of the data thus presented. This hypothesis will be tested by the Arco-Marathon #1 P. Gibbs well which has been drilled at the crest of the Fairview Anticline (Plates 1 and 4) to a depth of almost 5500 meters.

Gravity modeling of the crust-mantle boundary tends to confirm refraction seismic data indicating a crustal root under the approximate position of the Rocky Mountain Trench. The modeled amplitude of this root is dependent on the density contrast used between lower crust and upper mantle.
The westward extend of Phanerozoic rocks in the subsurface west of Glacier National Park is problematic. It appears that Phanerozoic hydrocarbon potential west of the Whitefish fault (Rocky Mountain Trench) is virtually non-existent. Hydrocarbon potential in Paleozoic rocks along the west side of Glacier National Park is good if substantial thicknesses have been preserved under the Hefty and Lewis plates. The Tertiary sediments in the Kishenehn basin and Rocky Mountain Trench may contain commercial hydrocarbon reserves if stratigraphic and structural development prove favorable.
### Explanation of headings

#### Identification
- **sta id**: Gravity identification.

#### Location
- **latitude**: North latitude in degrees minutes and hundredths of minutes.
- **longitude**: West longitude in degrees, minutes, and hundredths of minutes.
- **ele**: Station elevation in feet.
- **st**: State where station is located.

#### Gravity
- **observed**: Observed gravity in milligals.
- **theoretical**: Theoretical gravity.

#### Corrections
- **terrain**: Terrain correction out to 166.7 km in milligals.
- **Bouguer**: Elevation correction in milligals.
- **curv**: Curvature correction in milligals.
- **special**: Not used.

#### Anomalies
- **free-air**: Free-air anomaly in milligals.
- **complete-Bouguer**: Complete Bouguer anomaly in milligals for designated densities.
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<th>GRAVITY</th>
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* Denotes possible bad data point.


Chandra, N. N. and Cumming, 1972, Seismic refraction studies in western Canada: Canadian Jour. Earth Sciences, v. 9, p. 1099-1109.


Harrison, J. E., Kleinkopf, M. D., and Obradovich, J. D., 1972, Tectonic events at the intersection between the Hope Fault and the Purcell Trench, northern Idaho: U. S. Geol. Survey Prof. Paper 719, 24 p.


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