Nature of the Wind River thrust, Wyoming, from COCORP deep-reflection data and from gravity data

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ABSTRACT

Critical data for the interpretation of Laramide structure, a major tectonic problem bearing on the formation of the Rocky Mountains, have been obtained by the Consortium for Continental Reflection Profiling (COCORP) in the form of deep crustal seismic-reflection profiles. The Wind River Mountains in Wyoming have been uplifted by the Wind River thrust, which can be traced on COCORP seismic-reflection profiles to at least 24-km depth with an average dip of 30° to 35°. This Laramide uplift is thus the result of extensive horizontal compression with a minimum horizontal displacement of 21 km and a minimum vertical displacement of 13 km. The crust appears to have deformed essentially as a rigid plate. Gravity anomalies across the uplift can be modeled by a thrust, with the same geometry as indicated by the seismic-reflection profiles.

INTRODUCTION

Because Laramide structure in Wyoming is unique, the name "Laramide" has been given to that particular tectonic style. Its origin has long been controversial. Laramide uplifts in Wyoming consist of broad asymmetrical anticlines in which the oversteepened limb is faulted. A major tectonic question is whether this foreland deformation is associated with shallowly dipping thrusts representing horizontal compression or with steep reverse faults representing vertical movements (Fig. 1). Dips of flanking faults are often easily determined at the surface, but interpretation is complicated by the possibility that shallow thrusts may steepen with depth (Fig. 1A) and that steep faults may flatten to shallow dips (Fig. 1D). As a result, attitudes of controlling faults at depth have been interpretative and have led to disagreement among geologists about the origin of Laramide structures (Berg, 1962; Blackstone, 1963; Eardley, 1963; Prucha and others, 1965; Sales, 1968; Stearns, 1971, 1975; Lowell, 1974; Couples, 1977; Dickinson and Snyder, 1978). The problem is one of fundamental importance to the understanding of the geology and the development of the central Rocky Mountains.

For this reason, a deep seismic-reflection profile across the Wind River Mountains was carried out by the Consortium for Continental Reflection Profiling (COCORP). COCORP was formed to conduct deep seismic-reflection profiling in order to further our scientific knowledge of the continental crust. Deep seismic-reflection profiling had been tested successfully on two other sites in the United States: Hardeman County, Texas (Oliver and others, 1976), and the Rio Grande rift, New Mexico (Oliver and Kaufman, 1976). Previous reflection results of Junger (1951) near the Wyoming border and Perkins and Phinney (1971) in the Wind River area indicated that deep crustal reflections might be expected. Our COCORP results show that the method was highly successful in tracing the Wind River thrust to depth and that a shallowly dipping thrust is the correct structural interpretation (Fig. 1E).

GEOLOGY

The Wind River Mountains are the largest Laramide uplift in Wyoming. They trend northwest-southeast with a length of 220 km and a width of 70 km. Precambrian rocks are exposed in the core of

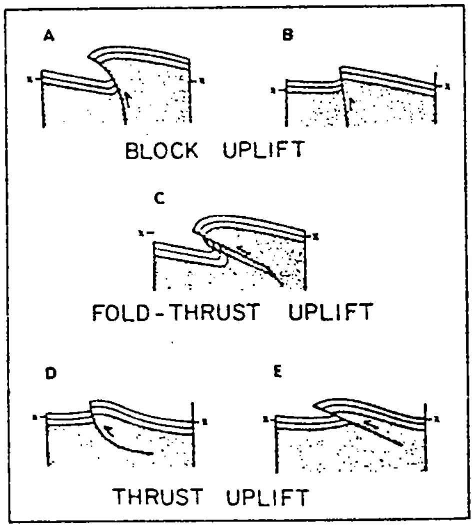

Figure 1. Postulated structural styles (attitudes) for the Wind River fault. Structure E or a structure between C and E is representative of the fault at depth; *x-x* represents the position of the present ground surface.

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the uplift. Maximum relief between the Precambrian basement in the Green River Basin to the southwest of the uplift and the Precambrian peaks in the Wind River Mountains is about 13 km. A near-surface geological cross section across the Wind River uplift shows that the horizontal sedimentary rocks in the Green River Basin to the west are overthrust by Precambrian rocks of the Wind River Mountains along a moderately dipping thrust plane. The northeast flank of the uplift is overlain by sedimentary rocks dipping at about 15° into the Wind River Basin. The dip of the thrust fault (near the surface) is about 20° to the northeast, as determined from shallow, seismic-reflection profiles (Berg, 1962) and from exploratory drilling through the overthrust Precambrian into the Green River Basin sediments. The Precambrian core of the uplift consists of migmatites at deeper levels in the center of the range and granitic intrusions and supracrustal rocks at higher crustal levels at the southeast end. These rocks constitute some of the oldest Precambrian crust in the United States and are dated at 2.7 b.y. B.P. (Naylor and others, 1970).

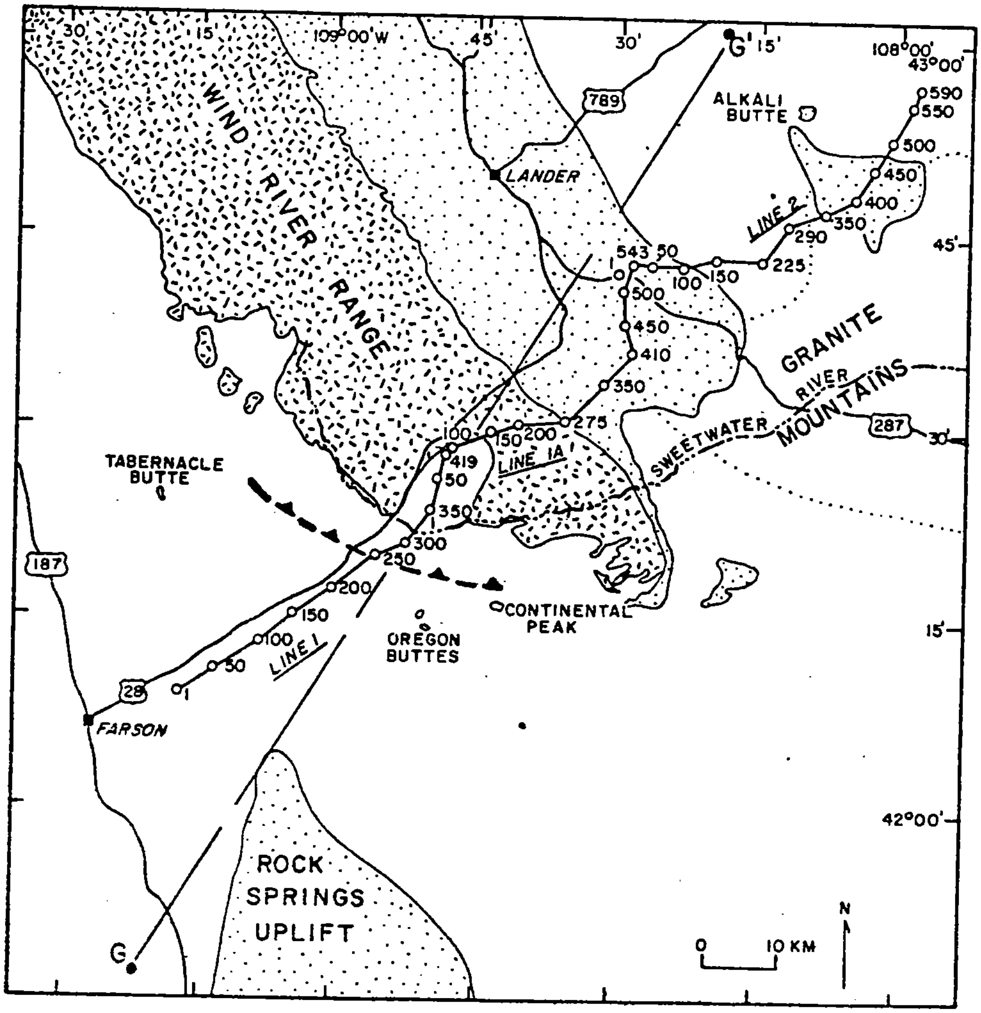

Figure 2. Location map of COCORP seismic-reflection profiles 1, 1A, and 2 traversing the southeast end of the Wind River uplift. Patterned area represents Precambrian outcrop. Stippled area is Paleozoic-Mesozoic outcrop, blank area is Tertiary, and dotted line outlines the Granite Mountains. Numbers along the lines represent station numbers. Dashed line indicates trace of Wind River fault in the region crossed by the profiles.

SEISMIC-REFLECTION INTERPRETATION

The COCORP seismic-reflection profile was laid out across the southeast end of the Wind River Mountains at South Pass, because this location offered the best accessibility (Fig. 2). Field work was carried out in the fall of 1976 and in 1977, and a total of 160 km of reflection profile was completed. Recording techniques were generally as described by Oliver and others (1976), except that in 1977, a 96-channel recording system was used instead of the 48-channel instruments used in earlier operations, and so maximum offset in the recording array was about 6.8 km in 1976 and 9.9 km in 1977.

The seismic section is presented in Figure 3 and is unmigrated so that it represents reflection data in time rather than in depth, and dipping events are not properly located spatially. Eastward dip in line 1A and line 2 (Fig. 4) is slightly exaggerated by the effect of velocity variations. The data were recorded to 20-s two-way traveltimes, or to a depth of over 60 km. Data quality is good, and numerous shallow and deep reflections are visible on the seismic profile (Fig. 3).

The most prominent feature of the profile is the group of strong horizontal reflections from the sedimentary section in the Green River Basin on the southwest (left) side of the profile (Figs. 3A, 4). Sedimentary rocks range in age from Cambrian through Tertiary and attain a maximum thickness of 9 km in the area of the seismic profile. The sedimentary rocks are gently folded and probably faulted in the Pacific Creek anticline (Fig. 4F) and in front of the Wind River thrust (Fig. 4B). Near the surface trace of the thrust, the data are of lower quality because of complex, near-surface structures and velocity variations.

The Wind River thrust appears clearly in the seismic section and truncates sediments over part of the section. From the initial steep dip, it flattens at shallow depths and then steepens at depth (Fig. 3E). The sedimentary rocks directly under the thrust are deformed by folding and numerous faults. A part of the apparent uplift of the sediments beneath the thrust in the time sections (Fig. 4B) is certainly velocity uplift. Velocity uplift is caused by a lateral velocity increase in seismic time sections and does not represent structure, but some structural uplift may also be present. Upturning of underlying sedimentary rocks into the thrust is not apparent (Figs. 3C, 4); sedimentary layering seems to continue directly into the fault, but a sharp bend or overturn at the thrust contact (as suggested by Berg, 1962) would probably not be visible on seismic-reflection profiles.

The thrust fault between basement and sediments can be clearly followed to 3.8 s (Fig. 3D) where the sedimentary section terminates. The fault, however, can be traced as a reflection past the deepest possibile sedimentary rocks (Fig. 3) and clearly continues to a time of about 9 s at 55 km (Fig. 4). Two-way traveltime may be converted to depth by multiplying by about 3 km/s; this corresponds to a

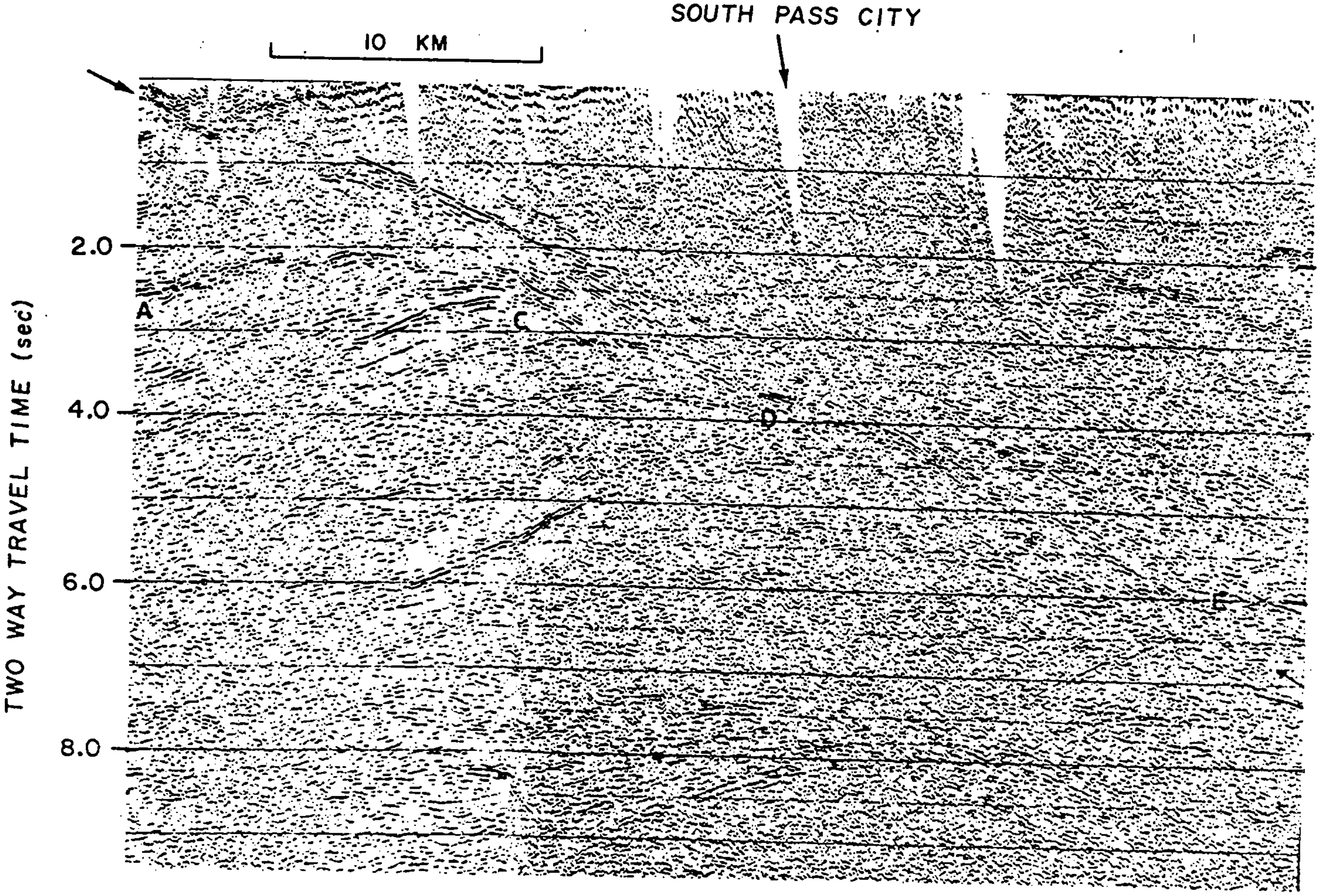

Figure 3. Unmigrated 24-fold CDP stacked reflection profile representing the upper portion of the Wind River thrust. Arrows define the position of the events representing reflections from the thrust plane. A = reflections from flat-lying sediments of Green River Basin. C = uplift (in line sections) of sedimentary reflectors under fault with no evidence of overturning. D = position of thrust against base of sediments. E = thrust reflection in the Precambrian crystalline rocks of the crust.

migrated depth of at least 24 km. *Because the same reflection that is identified as the thrust in sedimentary rocks can be followed continuously through most of the crust, we correlate this event with the Wind River thrust.* The thrust appears as a more or less continuous reflector between Precambrian crystalline rocks of the crust (Figs. 3E, 4). Small bends in the line direction (Fig. 2) do not strongly influence the dip of this event; this indicates that the event is not caused by energy from events lying outside the line of section. The event continues with essentially the same dip to about 6.5-s two-way traveltime where the dip decreases. We continue the fault to 8.7 s or about 24-km depth when migrated. Weak evidence for extending it to 9.5 s or 26 km exists. Any possible deeper continuation to 12 s is obscured by multiple reflections. Reasonable velocity estimates obtained from stacking give a general fault dip of 30° to 35° through most of the crust after migration. The COCORP seismic-reflection profiles also contain other events with dips subparallel to the Wind River thrust and that can be traced to similar depths as the Wind River thrust. Some of these events may be multiple reflections obscuring any primary events. There may be other thrusts that are related to the Wind River thrust but that do not crop out. If this is the case, the crust under the Wind River uplift may well be cut by more than one thrust fault.

The seismic data corresponding to other parts of the crystalline crust show numerous events. The upper crust does not show many reflectors (Fig. 3), but the middle to lower crust shows abundant reflections (Figs. 3, 4) that indicate a complex structure. These commonly have low dips of about 5° to 10°, but higher dips up to 30° are also found. These abundant deep reflections emphasize the heterogeneous and complex nature of the crystalline crust. These data will be described and interpreted in more detail in subsequent papers.

GRAVITY INTERPRETATION

The large positive gravity anomalies associated with Laramide uplifts in Wyoming (Berg and Romberg, 1966; Malahoff and Moberly, 1968) show that mass excess in the crust results from Laramide faulting. Thus, gravity interpretation could help to resolve the nature of Laramide flanking faults. For this reason, a gravity survey was conducted over the southern part of the Wind River Mountains. About 500 gravity measurements were completed during the summer of 1977, including some in the nearly inaccessible Precambrian core of the mountains. Gravity measurements were reduced to obtain simple Bouguer gravity anomalies by standard techniques (Dobrin, 1976). These Bouguer gravity values form the basis for a gravity profile from Farson to Riverton approximately parallel to the seismic profile. Bouguer anomalies range from −235 mgal in the Green River Basin to a maximum of −148 mgal in the Pre-

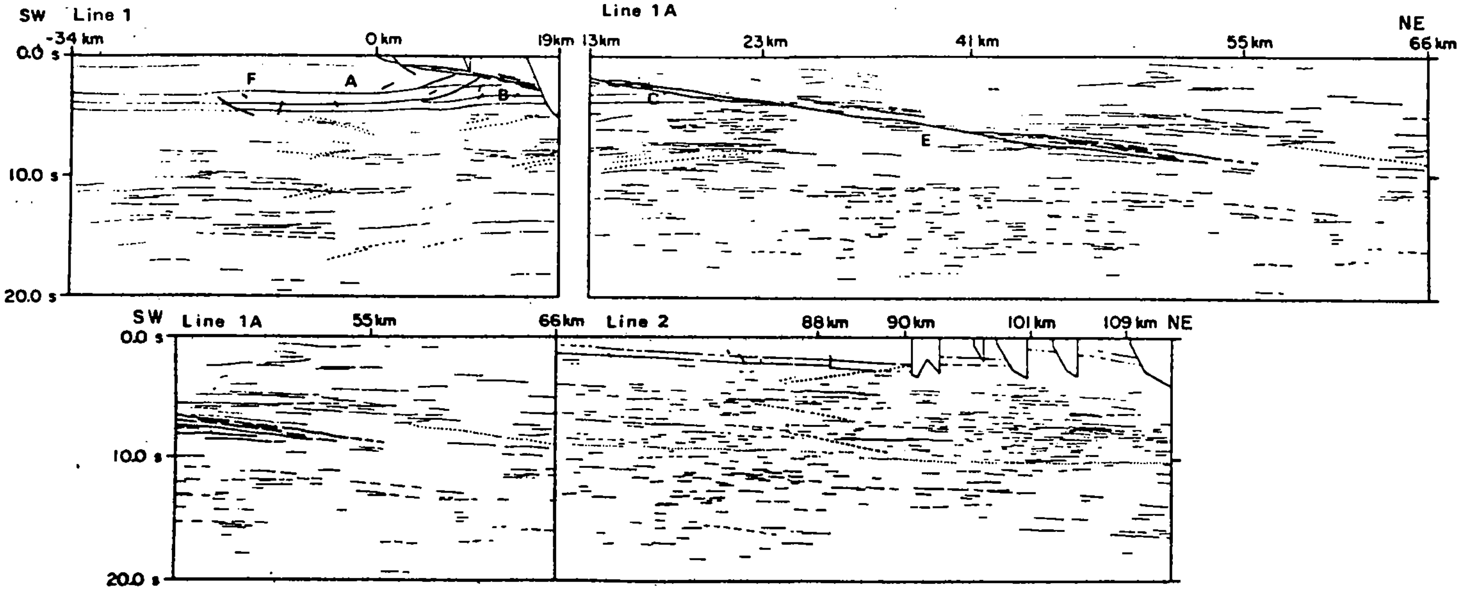

Figure 4. Interpretation of events seen on all three COCORP profiles. There is an overlap from the top northeast to bottom southwest parts of the diagram. The position of the Wind River thrust at the surface is represented by 0 km. The profiles were recorded to 20-s two-way traveltime. Dashed events represent diffractions or off-line reflections. A = reflections from flat-lying sediments of the Green River Basin. B = uplift (in time sections) of sediments underlying the Precambrian thrust over them by the Wind River thrust. C = termination of sedimentary layers against thrust with no evidence of overturning. E = appearance of thrust in the Precambrian crystalline rocks of the crust. Dotted lines represent enigmatic low-frequency event.

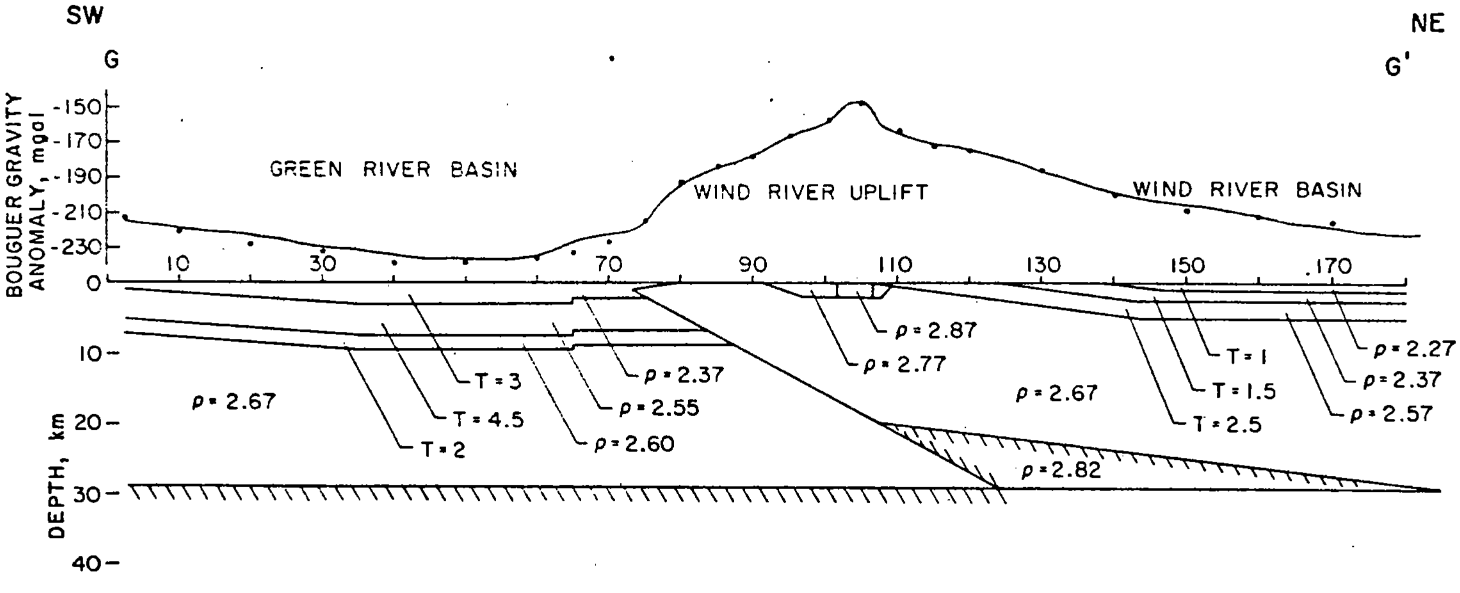

Figure 5. Bouguer gravity anomalies and calculated model. Horizontal and vertical scale in kilometres. T = thickness of layers in kilometres; ρ = density in g/cm^3. Continuous line represents observed gravity. Dots represent modeled gravity.

cambrian core of the uplift, and back down to −220 mgal in the Wind River Basin.

Density of sedimentary rocks has been determined from formation density logs and ranges from 2.2 to 2.6 g/cm^3. Density is strongly dependent on depth as well as rock type (Malahoff and Moberly, 1968). Densities of Precambrian rock range from 2.65 to 3.00 g/cm^3.

The major feature of the gravity profile is the large increase in gravity over the Precambrian core of the uplift. Much but not all of this increase is caused by the contrast of low-density sedimentary rock against higher-density Precambrian rocks where sedimentary basins adjoin Precambrian uplift. Excess positive gravity anomalies must be caused by some deeper source. This deeper source is probably associated with faulting, so that the position of the fault from the seismic section logically fixes the geometry of the uplifted mass excess to a depth of a least 24 km.

Bouguer gravity anomalies have been modeled using geologic control and the seismic section for basin geometry and the seismic interpretation for geometry at depth. After accounting for the gravity effect of low-density sediments against Precambrian basement, the additional positive anomaly might be caused by uplift of denser lower crust and/or uplift of upper-mantle material along the fault. Both possibilites have been modeled, but the observed profile can best be fit by the gravity effect of uplifted lower crust (Fig. 5). If the effect of uplifted mantle is modeled, its gravity effect is shifted too far to the northeast to fit the observed profile. Use of different densities for sedimentary basins might allow gravity models representing steeper faults to be used, but steeper faults would conflict with the seismic interpretation. A knowledge of Moho depth along this profile would aid our interpretation, but this information is not known. The nearest refraction profile (Braile and others, 1974) places the Moho at 40-km depth some distance to the northwest.

Several important conclusions may be drawn from the gravity interpretations. Dense material must be upfaulted or intruded underneath the uplift. The gravity model which is based on offset of denser lower-crust material along the fault (that is, modeling the seismic interpretation) agrees best with the observed gravity field. Finally and most interestingly, the fault probably does not offset the Moho enough to cause an appreciable gravity anomaly. The thrust may decrease in dip and parallel the Moho, or any Moho offset may have flowed out to an equilibrium position.

CONCLUSIONS

These studies have produced data critical to interpretation of Laramide structure. The Wind River thrust can be followed in the seismic-reflection section to a depth of at least 24 km with a dip of 30° to 35°. This proves that structure E or something between C and E in Figure 1 is the correct interpretation, at least for this Laramide uplift. High-angle reverse faulting can be ruled out. Deformation took place as a major low-angle break through most of the crust as though the crust behaved like a thick slab. This deformation must be caused by horizontal compression. Considerable crustal shortening has taken place and probably is related to major plate movements. Gravity interpretation supports the seismic interpretation by showing that the fault must dip moderately and that dense rocks in the deep crust must be displaced. Near the base of the crust, the fault may flatten to parallel the Moho. Any appreciable offset of the Moho may have been removed by subsequent creep down to a common level.

Besides the depth and dip of the fault, the most astounding aspect of this study is the ability of the seismic-reflection method to trace directly a moderately dipping fault through most of the crust. This result has important practical and scientific implications. The seismic-reflection method should have great potential to trace active faults that are not too steeply dipping, if an adequate contrast in acoustic impedance exists. The ability to resolve thrusting in crustal sections formed from ancient island arcs and crustal thickening by underthrusting of slabs at deep crustal levels will have exciting implications for crustal genesis.

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