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STRUCTURE OF THE LARAMIDE WIND RIVER UPLIFT, WYOMING, FROM COCORP DEEP REFLECTION DATA AND FROM GRAVITY DATA

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Abstract. The question of the structure of the Wind River uplift, a Laramide foreland structure in Wyoming, has been answered by Consortium for Continental Reflection Profiling (Cocorp) deep crustal reflection profiling and by gravity interpretation. Wyoming uplifts are asymmetrical anticlines whose steep limb is commonly cut by a reverse fault or thrust. If the thrust continues into the crust with low dip, the uplift is caused by horizontal movements; and if the fault steepens into a high-angle reverse fault in depth, the uplifts are caused by vertical movement. The Wind River uplift is the largest of the Laramide structures in Wyoming, and the thrust fault has 14 km of vertical separation and 26 km of horizontal separation. About 168 km of crustal reflection profiling has been completed by Cocorp across the uplift. The Wind River thrust fault generates a continuous reflection from near the surface to a depth of about 24 km, and the thrust appears as a complex zone of faults. Apparent dip of the thrust is 30°-38°, and true dip may be up to 48°. Interpretation of deep crustal reflections is complicated by the presence of multiple reflections. A structure whose complexity approaches that of basement outcrops is found in the deep crust. Gravity modeling also suggests that the fault dips moderately and that dense rocks are uplifted in the deep crust. The Moho does not seem to be presently displaced by faulting. The crust in the Wind River uplift began to deform by large-scale folding and then broke and faulted as a rigid slab. Faulting is caused by crustal shortening from compression that is related to plate movements.

Introduction

Laramide basement uplifts in Wyoming exhibit such a distinct structural style that the area has been called the Wyoming Province of the American Cordillera [Prucha et al., 1965]. The origin of these faulted basement-cored anticlines is a major question in tectonics, as is the development of these features within a plate tectonics framework. Laramide uplifts in Wyoming consist of broad asymmetrical anticlines in which the oversteepened limb is faulted, and the Wind River Mountains are the largest of these structures. Dips of the flanking faults may be readily determined at or near the surface, but interpretation is complicated by the possibility that gently dipping thrusts may steepen with depth or that steep reverse faults may flatten to shallow dip (Figure 1). As a result the geometry of flanking faults at depth and the resulting movement picture have been interpretive and have led to controversy among geologists about the importance of horizontal versus vertical movements [Sanford, 1959; Berg, 1962; Blackstone, 1963; Prucha et al., 1965; Sales, 1968, Stearns, 1971, 1975; Lowell, 1974; Couples, 1977; Matthews, 1978]. The problem is one of fundamental importance for understanding the structure and origin of the central Rocky Mountains.

For this reason a deep seismic reflection profile was completed across the Wind River Mountains by the Consortium for Continental Reflection Profiling (Cocorp). Cocorp was formed to conduct deep reflection profiling in order to further our basic scientific knowledge of the continental crust. Deep seismic reflection profiling, based on seismic prospecting techniques with operating parameters optimized, had been tested successfully on two other sites in the United States: Hardeman County, Texas [Oliver et al., 1976] and the Rio Grande rift, New Mexico [Oliver and Kaufman, 1976]. Because of the great size of the structure and its tectonic importance the Wind River Mountains of Wyoming were chosen by Cocorp to solve a major geologic problem. A preliminary account of the study has been given by Smithson et al. [1978]. The results of this study are presented here in detail and have many exciting implications.

Seismic reflections from within the crust itself in this general area were first observed by Junger [1951] during normal seismic prospecting for petroleum. The fact that these were observed near the Wyoming border encouraged

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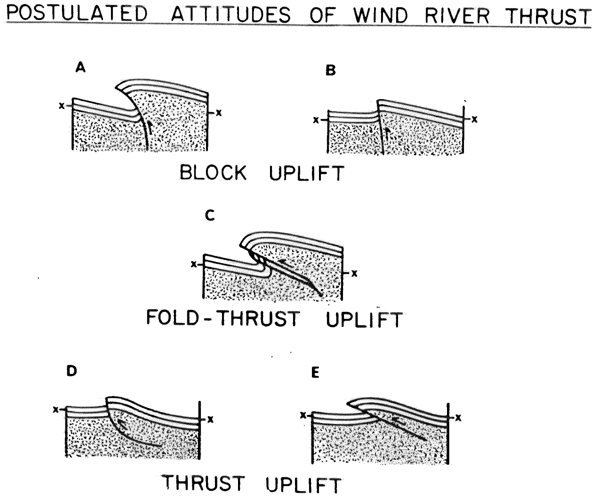

Fig. 1. Proposed structural styles for the Wind River fault. Structure between that in Figure 1c and in 1e is representative of the fault at depth; x-x represents the position of the present ground surface.

Cocorp that further reflection studies in the area might be successful. Perkins and Phinney [1971] obtained reflections at isolated sites in the vicinity of the Wind River uplift. Crustal reflection studies have been extensively carried out with success in Europe [Dohr and Meissner, 1975] and in Canada [Cumming et al., 1968]. Formation of the Cocorp project presents the first major effort toward crustal reflection profiling in the United States and is an endeavor conducted on a greater scale than has hitherto been attempted.

Geology

The northwest-southeast trending Wind River Mountains are the largest Laramide uplift in Wyoming (Figure 2) and have a length of 220 km and a width of 70 km. They are a broad simple anticline affecting Paleozoic through Early Tertiary rocks and cored by Precambrian rocks. A thrust fault borders the Wind River Mountains on the southwest, where the Precambrian core of the uplift has overridden the almost horizontal rocks of the Green River Basin. 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 [Prucha et al., 1965]. The size of this relatively simple structure was a major factor in deciding to study the area with deep seismic reflection profiling. 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 belt near the surface is about 20° to the northeast as determined from industry shallow reflection profiles and from exploratory drilling through the overthrust Precambrian into the Green River Basin sedimentary rocks [Berg, 1962].

A geologic cross section along the line of the seismic profile (Figure 3) shows that almost horizontal sedimentary rocks continue in the Green River Basin to the Moxa arch and the overthrust belt in westernmost Wyoming. The Pacific Creek anticline is a faulted gentle fold in the basin in front of the Wind River thrust (Figure 3). The Wind River thrust cuts off the sedimentary rocks of the Green River Basin and places Precambrian rocks above these sedimentary rocks. The area under the thrust overhang is commonly a target for petroleum exploration, so a number of boreholes start in Precambrian rocks, penetrate the thrust, and bottom in the underlying sedimentary rocks. These underlying sedimentary rocks may be turned up into the thrust according to borehole information and many interpretations [Berg, 1962]. This indicates that folding progressed to the point of overturning one limb before thrusting took over. Geometry of the sedimentary rocks over the Wind River uplift is interpreted differently according to one's views on the style of deformation [Berg, 1962; Prucha et al., 1965]. Sedimentary rocks dip gently off the Precambrian core at 12°-15° into the Wind River Basin [Keefer, 1970]. The seismic profile crosses a series of small tight Laramide folds in the Wind River Basin. These are the Sheep Mountains anticline, the Sand Draw anticline, the Rogers Mountain anticline, and the Conant Creek anticline [Keefer, 1970, Plate 2]. The Wind River thrust is a huge feature involving at least 13 km of vertical separation and 20 km of horizontal separation.

Much discussion in the literature centers around the attitude of faults flanking Laramide uplifts and on the forces that caused the deformation. Both shallow and steeply dipping faults are observed at the surface, but different workers have interpreted different attitudes at depth. Eardley [1963] suggests that vertical uplift forming these structures was caused by intrusion of basaltic magma deep in the crust. Berg [1962] suggested that the Wind River Mountains formed as a giant fold-thrust, and Blackstone [1963] noted that Laramide uplifts probably formed from compression but also showed features resulting from vertical uplift. Prucha et al. [1965] believed that Laramide faults steepened with depth and were the result of vertical uplift. Sales [1968] suggested that the Wyoming province basically developed from compression associated with left lateral shear and that the Colorado Plateau formed a buttress that developed horizontal shear in Wyoming to form the divergent Laramide structures. Stearns [1971, 1975] has championed an origin by vertical movements, and Couples [1977] has worked on the problem mathematically. Lowell [1974], Burchfiel and Davis [1975], and Dickinson and Snyder [1978] proposed explanations for Laramide structure within a plate tectonics framework.

The Precambrian core of the uplift consists of migmatites representing deeper levels in the center of the range and granitic intrusions into supracrustal rocks at higher crustal levels down the plunge of the structure at the southeast end. The supracrustal rocks consist of gneisses and schists that are called metaironstone, metaandesite and metagreywacke [Bayley et al., 1973]. These rocks are strongly folded and dip steeply. Condie [1972] suggested that an Archean greenstone belt, right along the Cocorp profile, marks an ancient suture zone. The Precambrian rocks constitute some of the oldest Precambrian crust

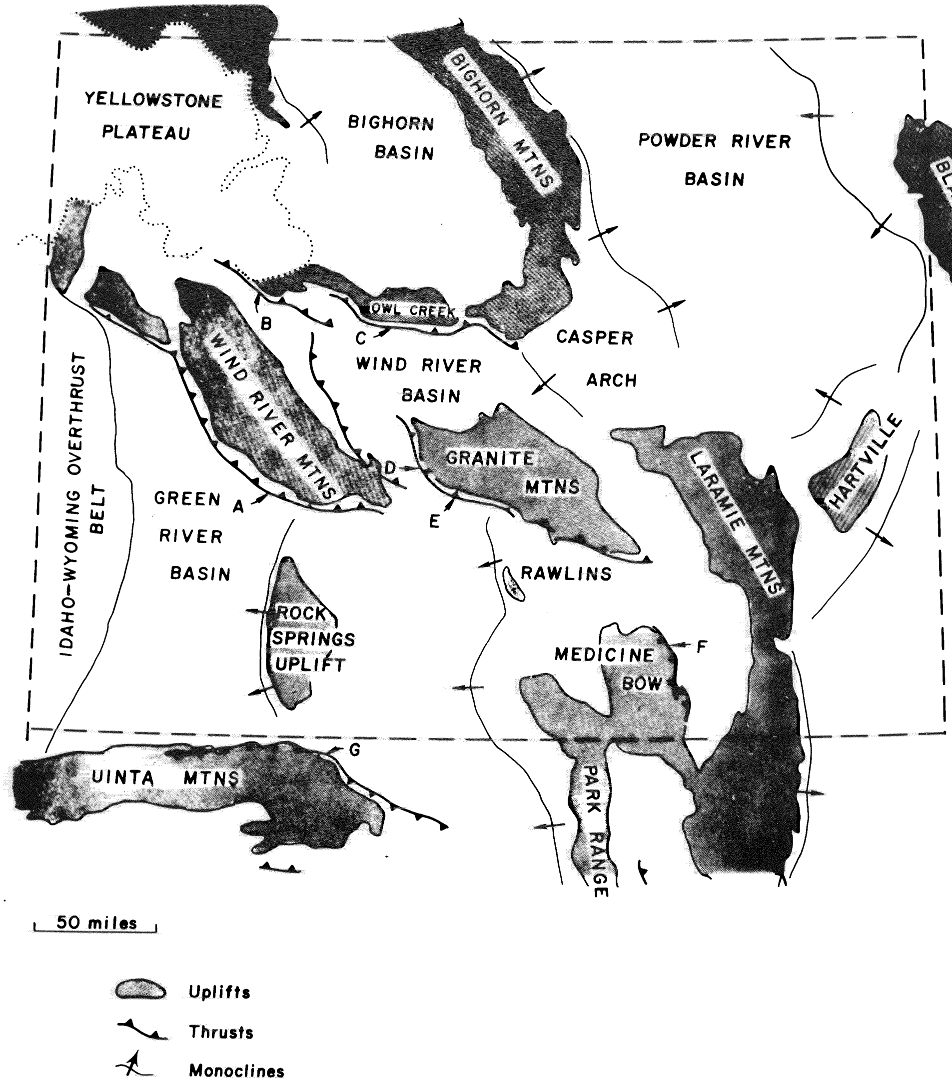

Fig. 2. Tectonic map showing basement uplifts in Wyoming.

in the United States, and an intrusion is dated at 2.7 b.y. B.P. [Naylor et al., 1970].

Previous Geophysical Data

Gravity studies of Wyoming uplifts include those of Berg and Romberg [1966]. Case and Keefer [1966], Malahoff and Moberly [1968], and Karasa and Smithson 1977 . Berg and Romberg [1966] modeled the Wind River thrust as a gently dipping thrust against sedimentary rocks. Case and Keefer [1966] showed that the Emigrant Trail thrust flanking the Granite Mountains also had a low dip. These gravity interpretations of Laramide faulting modeled Precambrian rocks thrust against sedimentary rocks and did not include deep crustal structure in their models. Malahoff and Moberly [1968] suggested that Laramide uplifts were undercompensated, and Karasa and Smithson [1977] showed that deep crustal material was involved in the faulting along the Granite Mountains adjacent to the Wind River Mountains.

Numerous shallow seismic reflection profiles have been conducted across the Wind River thrust by the petroleum industry. Industry data demonstrated that the Wind River thrust could be mapped against sedimentary rocks by reflection profiling. Berg [1962] used early seismic reflection data for his interpretation of shallow Wind River structure.

Crustal refraction data on the position of the Moho are not available for the immediate vicinity of the Cocorp profile. An unreversed crustal reflection profile [Braile et al., 1974] gives an estimate of 40 km for Moho depth 90 km to the north, and Perkins and Phinney [1971] obtained deep crustal reflections in the area. Another refraction profile gives a crustal thickness of 40 km for southwestern Wyoming [Prodehl, 1970]. These values are used for approximate estimates of crustal thickness, but a reliable value is not known along the Cocorp profile. Knowledge of Moho configuration is obviously critical for an understanding of tectonics in this region.

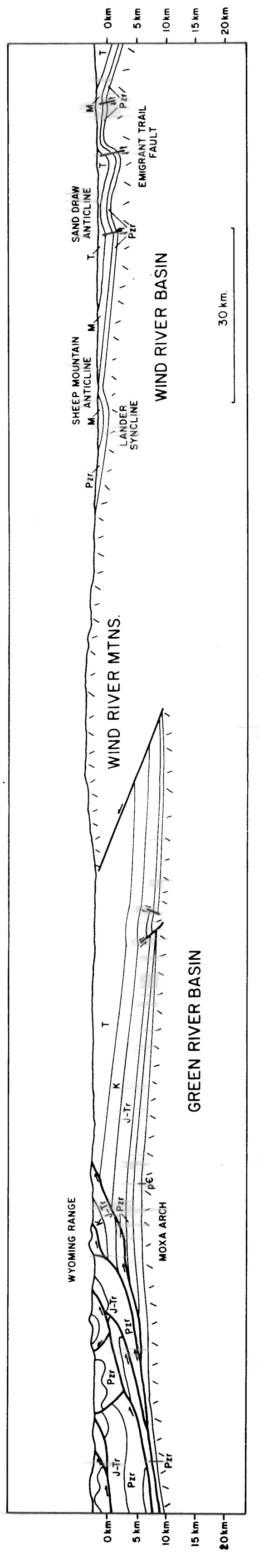

Fig. 3. Structural cross section showing structure of Wind River uplift and the adjacent basins [after Keefer, 1970; Royce et al., 1975].

Data Acquisition

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 (Figure 4). Field work was carried out in the fall of 1976 and 1977, and a total of 168 km of 24-fold common depth point reflection profile was completed, consisting of lines 1, 1A, and 2 (Figures 5, 6, and 7). Recording techniques were generally as described by Oliver et al. 1976 . Exceptions are that in 1976 a 48-channel recording system and 134-m station interval were used (line 1) and in 1977 a 96-channel recording system and 100-m station interval were used (lines 1A and 2). Maximum offset was therefore 6.8 km in 1976 and 9.9 km in 1977). Listening time was 50 s; a 20-s sweep in 1976 gave a 30-s record, and a 30-s sweep in 1977 gave a 20-s record. The longer sweep was used to put more energy into the ground. The sweep frequency was 8-32 Hz. Five synchronized vibrators operated in line and used 16 sweeps per source point. These 16 separate sweeps were stacked in the field to obtain the field record from one source point. Some large gaps are present in the data, particularly in line 2, where producing oil fields in anticlines generated too much noise on the local traces. The other important noise source was wind.

Data Processing

Processing and interpretation of deep crustal reflection data involve special considerations that are not encountered in shallower reflection data. These considerations are lower reflection coefficients and complex structure of Precambrian reflectors and the short length of the recording array with respect to the depth of desired signals. These factors weaken velocity analysis in the crust beneath sedimentary rocks and discrimination against multiple reflections at longer record times.

For these reasons, each line was first studied by generating constant velocity sections for the entire line at velocities from 11,000 (ft/s) (3.35 km/s) to 25,000 ft/s (7.62 km/s) at intervals of 2000 ft/s (0.61 km/s). The constant velocity sections offered the following advantages: (1) They could be used to visually estimate stacking velocities at depths where velocity spectral analyses were unstable. (2) Complex structures and anomalous events with high dip whose stacking velocity could be entirely unrelated to rock velocity were empirically enhanced. (3) Multiple reflections could be studied. The constant velocity sections were visually analyzed for estimates of best stacking velocity. These stacking velocities cannot be used to obtain interval velocities for rock identification. Dipping events often were enhanced at higher velocities totally unrelated to any true rock velocity; for example, the Wind River thrust appeared strongest in a section stacked at 25,000 ft/s (7.62 km/s).

Stacking velocities vary greatly in the shallow section where Tertiary sediments (V = 3.35 km/s) are replaced by crystalline basement rocks (V = 5.79 km/s) in the Wind River uplift. Deep

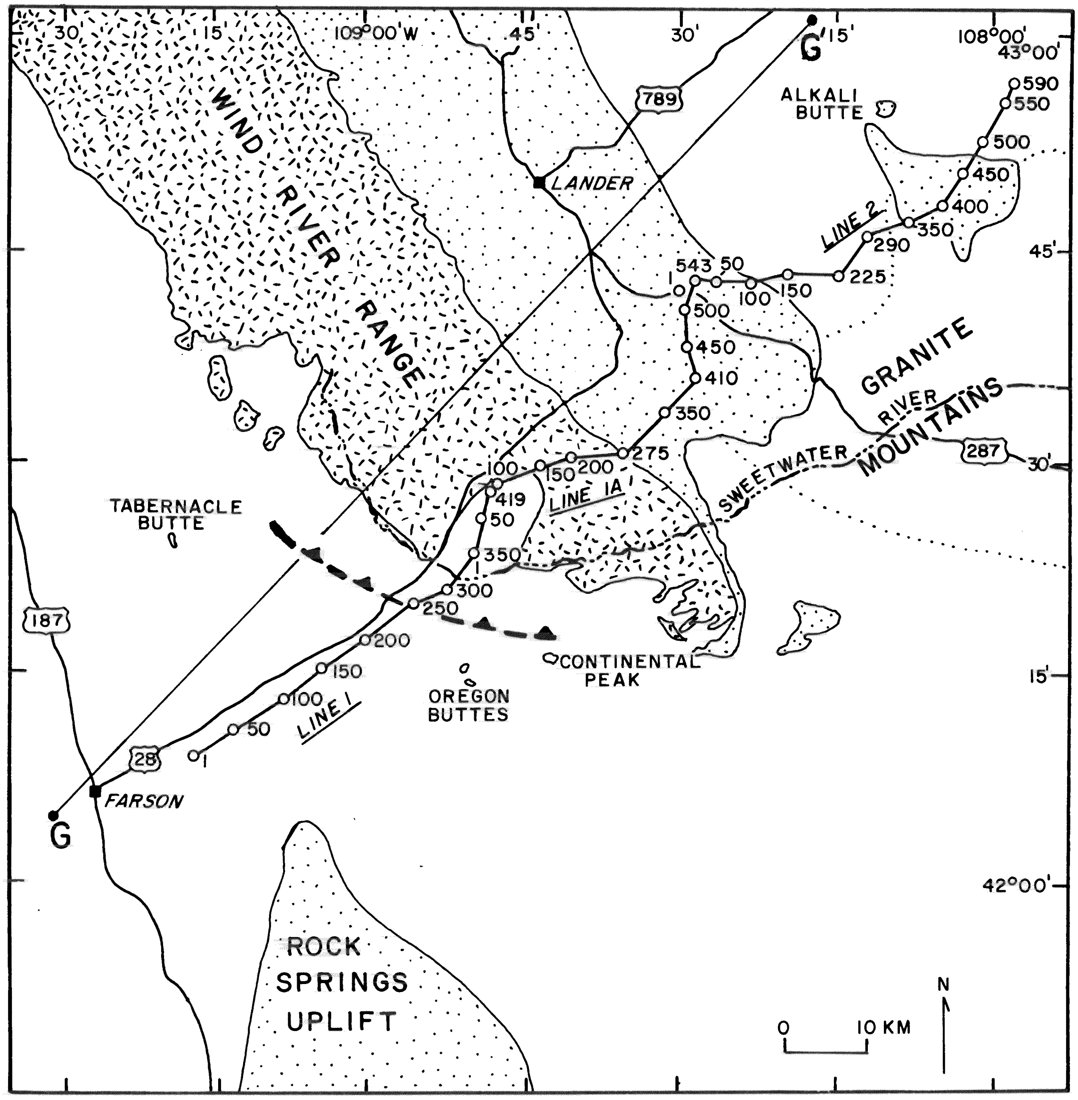

Fig. 4. Location map of Cocorp seismic reflection profiles 1, 1A, and 2 traversing the southeast end of the Wind River uplift. Hatched area represents Precambrian outcrops. Numbers along the lines represent station numbers. Barbed line indicates trace of Wind River fault in the region crossed by the profiles. G-G' is line of gravity profile.

stacking velocities are high (6-7 km/s) because of high velocities associated with crystalline crustal rocks. Some velocity control is provided by velocity surveys from a borehole in crystalline rocks of the Wind River Mountains [Smithson and Ebens, 1971] and from a borehole to Lower Cretaceous rocks in the Pacific Creek anticline.

After stacking, filtering, deconvolution, correction to a 2000-m flat datum, and residual statics were applied to obtain a final section. Further processing included autocorrelation, narrow band filtering, near- and far-trace stacks, migration, frequency analysis, and signal-to-noise ratio analysis. Static corrections may not be a significant problem for the data quality; however, complex wave paths were a problem, particularly in the vicinity of the thrust fault where playouts of CDP gathers showed that the stack was not largely in phase. In this area the near-trace stack gave somewhat better data quality. A near-trace stacked section was also used to analyze for multiple reflections, which were enhanced on this section. Deconvolution with a 560-ms operator was effective to remove short-period reverberations that were especially strong just above the thrust fault, where a thin section of low-velocity Tertiary sediment directly overlies high-velocity Precambrian basement. Autocorrelation demonstrated the presence of moderately strong multiple reflections with periodicity of 0.5-1.0 s on line 1. Migration was difficult to carry out at these long record times, but a wave equation migration of line 1 did improve the shallower data and help with interpretation of some faulting and possible multiple reflections.

Frequency analysis reveals that the frequency content of reflections varies vertically and horizontally. As we would expect, a signal from greater depth has a lower frequency spectrum, and shallower reflections have a higher frequency content. But also reflections are distinctly

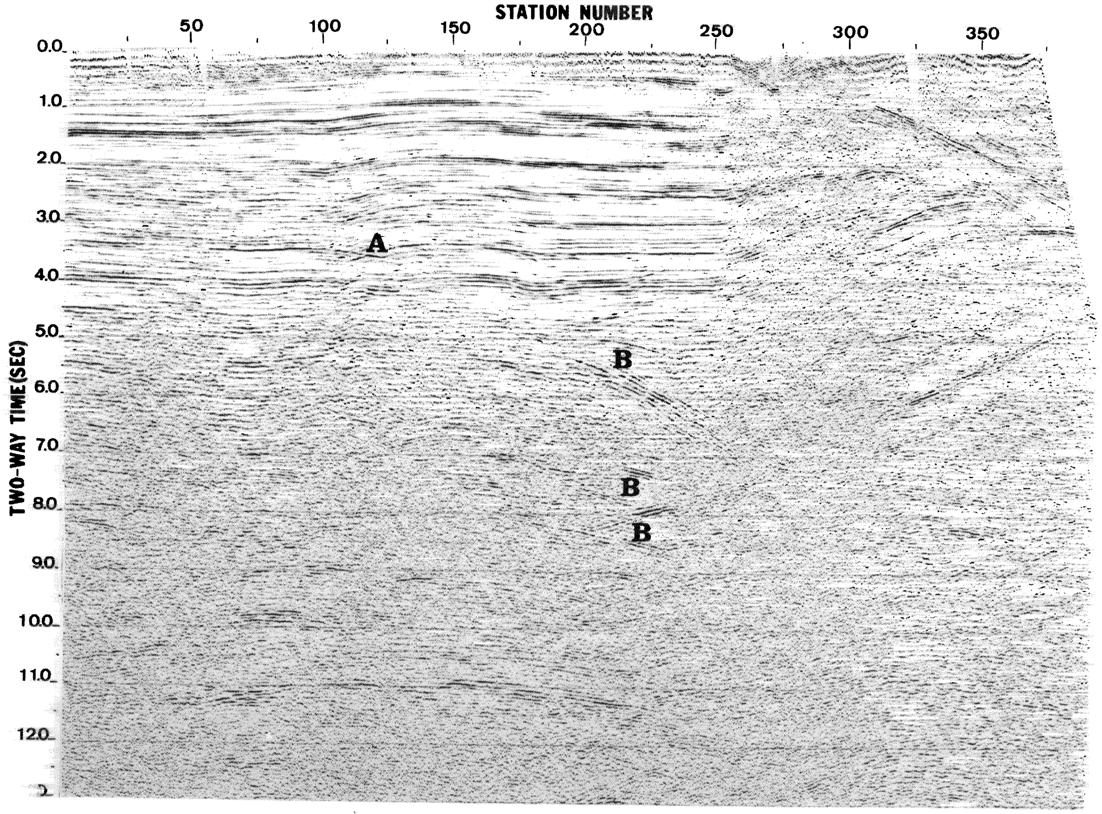

Fig. 5. Unmigrated 24-fold, CDP-stacked Cocorp reflection profile showing line 1. Station numbers along top. Flat lying sedimentary rocks of Green River Basin from surface down to 4.0-4.5 s. Excellent data quality ends at station 250, where the Wind River thrust approaches the surface, bringing a wedge of Precambrian crystalline rocks above sedimentary rocks. Pacific Creek anticline is clearly visible in the sedimentary rocks at station 150. A syncline on the west side of the anticline gives the characteristic bow tie effect of a syncline with a buried focus (A). Highly dipping events (B, 5-9 s) may be reflections from outside the plane of the section (sideswipe). Strong reflections continue down to 11 s.

higher peak frequency (about 12-15 Hz versus 20-25 Hz) at 9-10 s in lines 1 and 1A, where Precambrian is exposed so that higher frequencies are usable in crystalline rocks.

Signal-to-noise ratio is variable probably because of wind on certain days, especially later in the fall on bases of coherence and noncoherent energy. A signal-to-noise ratio of 1 is reached at about 15 s on line 1, 13 s on line 1A, and 10 s on line 2. The data is presented unmigrated in time sections so that true position and geometry of structures are distorted. Readers should note that seismic time sections do not show the true position or even the true geometry of reflectors and that interpretation may be complicated by events arriving obliquely from outside the plane of the section.

Anomalous Events

Anomalous events on the seismic sections include multiple reflections, reflected refractions, diffractions, energy from events arriving outside the plane of the section, and possibly converted waves. Of these, multiple reflections are the most common and constitute a significant part of the events in parts of lines 1 and 2.

Recognition of multiple reflections on a broad scale is based on two criteria: (1) general parallelism of deep reflections with surface structure in sedimentary rocks (Figures 5 and 7) and (2) the total change character of seismic sections between lines 1 and 2 (Figures 5 and 7), where sedimentary rocks cover the surface, and line 1A (Figure 6), where Precambrian rocks crop out. In lines 1 and 2, reflections as deep as 10-12 s mirror the dip of sedimentary rocks in the first 2-4 s. The resulting broad pattern is that numerous closely spaced horizontal reflectors are found between 4 and 12 s on the left-hand side of line 1 (Figure 8). Here the basement is at 4.5 s or less. The nature of the multiple problem is clearly illustrated by observing a typical 'bow tie' pattern from a syncline with a buried focus (Figure 9). This pattern occurs at 3.5 and 4.0 s as primary reflections and is repeated as multiple reflections at 6-7 s, a time far below the base of the Cambrian in this area. These multiple reflections appear best on the near-trace stack (Figure 9) where the normal-moveout of the multiples is too small for them to be cancelled. Multiples repeated at 400-600 ms suggest that events are being repeated by a relatively short path which may be in the near surface. Similarity in character between horizontal events from 5 to 12 s

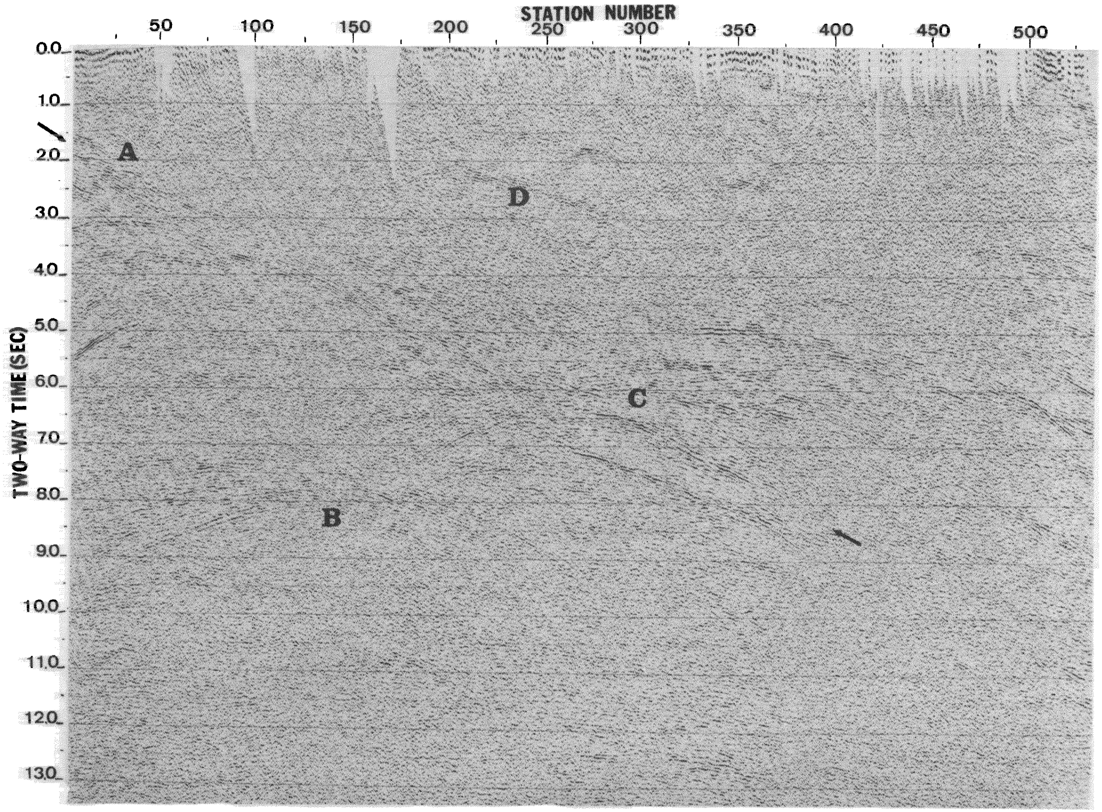

Fig. 6. Cocorp reflection profile showing line 1A. Wind River thrust (arrows) is a continuous reflection to 9.0 s or 24 km. Strong reflection (A, upper left) marks wedge of Precambrian crystalline rocks overlying sedimentary rocks to 3.9 s. Velocity uplift, complex faulting, and possibly folding in sedimentary rocks under the thrust. Precambrian rocks exposed at the surface from stations 100 to 175 of line 1A. Complex Precambrian structure in the deep crust (B at 8 s, C at 6 s) may be correlated across the fault. Strong shallow reflection (D) in Precambrian crust.

and those in the sedimentary section is striking (Figures 8 and 9). Likewise, the dipping events on the left side of line 2 (Figure 7) strongly mirror structure in sedimentary rocks and probably are multiple reflections. A dead zone for about 2 s beneath the sedimentary reflections here probably represents the time interval in which the CDP filter is successfully cancelling multiples and in which trace amplitude is decreased by automatic gain control. In sharp contrast is the general appearance or character of reflections in the middle part of line 1A (Figure 6). Here the reflections are much less common and weaker and show divergent dips and less regular character, exactly what would be expected from complex basement rocks. Theory tells us that any multiple reflections should decrease rapidly in amplitude. The strength of these multiple reflections is probably caused by constructive interference within the multiple-generating system. Certainly, this area, which has been well prospected, is not known to be a problem area for multiples caused by certain high-amplitude reflectors [Ellsworth, 1948; Mouritsen, 1963] that interfere within the sedimentary reflections. Reflection coefficients for single interfaces are up to 0.3 in sedimentary rocks and 0.13 in crystalline rocks. When we consider the capability for much stronger reflections in the sedimentary section, sedimentary multiples may overwhelm primary reflections from within underlying basement, whereas such multiples would simply go unnoticed within record times for sedimentary rocks.

Reflected refractions seem to be a common kind of noise associated with faulted anticlines in Laramide structures. These events are typically caused by a refraction from a high-speed layer hitting a reflector such as a fault and reversing their path along the high-speed layer to return to the surface as a head wave. They appear as crosscutting events with high constant dips [Swartz and Lindsey, 1942]. Good examples are found in the middle of line 2 (Figure 7), where an event dipping steeply to the left comes off the Sand Draw anticline. It has an apparent velocity of 5.9 km/s and probably corresponds to a refraction that was reflected from the reverse fault in the Sand Draw anticline along the top of a sedimentary layer. A similar event at 5 s beneath the Wind River thrust (Figure 10) has an apparent velocity of 7.0 km/s and may be a primary event representing important structure such as a crustal flake [Oxburgh, 1972] related to the fault, or it may be a reflected refraction or other anomalous event such as a reflection that traveled a complex path underneath the Precambrian fault wedge.

Energy from a reflector lying outside the plane of the section (sideswipe) [Tucker and

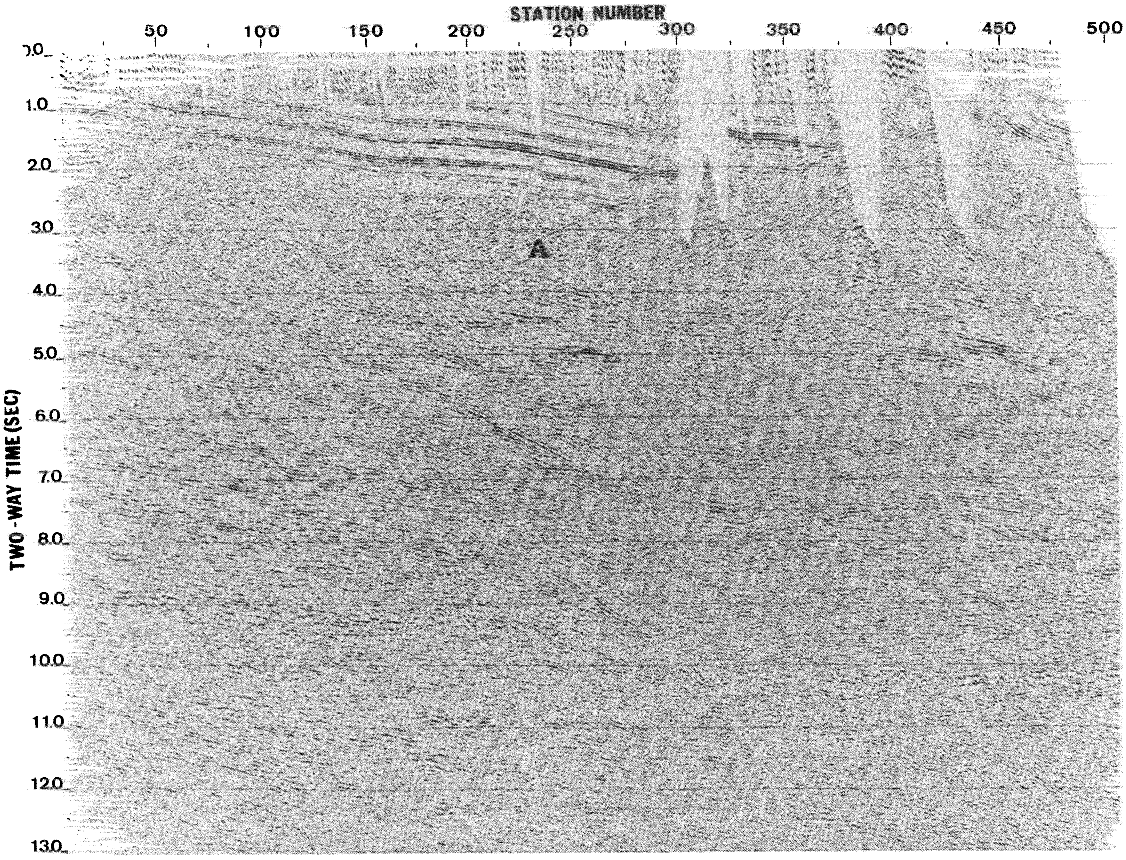

Fig. 7. Cocorp reflection profile showing line 2. Sedimentary rocks dip off the gentle NE flank of the Wind River uplift from 1.0 s (station 0) to 2.5 s (station 275). Sand Draw anticline at station 300 and Rogers Mountain anticline at station 375. Events with constant high dip (station A) may be reflected refractions from a fault in the Sand Draw anticline. Diffractions from faults are also present. Numerous dipping events below 4 s in the deep crust.

Yorkston, 1973] may be common in our data; in fact, such events from dipping reflectors should be common in crustal reflections. Unless such side-arriving energy comes from near-surface features such as cliffs or faults, it constitutes signal and contains important information. Because we do not, as yet, have crosslines, we cannot recognize side-arriving energy. High-dip events in the middle of line 1 between 5 and 9 (Figure 8) may be from outside the plane of the section, or they may also be diffractions in part. Diffractions also occur in faulted sedimentary rocks underneath the Wind River thrust and from faulted anticlines on line 2 (Figure 7).

One of the most unusual events in our data or in any seismic section is a low-frequency event of about 8 Hz on line 2 (A-A' in Figure 11). The event continues across line 2 between 8 and 10 s dipping to the northeast and exhibits a characteristic 'wobble' or irregular arrival time. The event is enhanced by deconvolution. On the CDP gathers for the final stacked section it only stands out on the far traces. It is tempting to call this a reflection from some unusual horizon, an event characteristic of the deep crust in this area; however, the NMO-corrected CDP gathers show that this event still has considerable move-out and only appears on the far traces. It is this move-out that contributes to its low-frequency character and wobble in the stacked section. This event is difficult to explain, but it may be a converted wave because the move-out is not appropriate for a reflection. This interpretation might explain consistent arrival times, low frequency, and greater-than-normal move-out. The event could also be a processing artifact.

Interpretation of Reflections

Sedimentary rocks. Excellent reflections are found in the sedimentary section (Figures 5, 6, 7, 10, 12, and 13) except in the vicinity of the Wind River thrust. The basement is at 4.0-4.5 s. The actual basement contact is probably masked by multiple reflections generated higher in the section. Reflections are correlated with formations down to Lower Cretaceous by means of a velocity survey in a borehole in the Pacific Creek anticline, the Superior No. 1 Federal. Deeper reflectors are tentatively correlated with Triassic, Jurassic, and Paleozoic formations. The Pacific Creek anticline (Figure 8) is the main structure in sedimentary rocks of the Green River Basin on line 1 west of the Wind River thrust (Figures 5 and 8). The Pacific Creek anticline is faulted on both flanks and is bordered on the southwest by a tight syncline with a buried focus

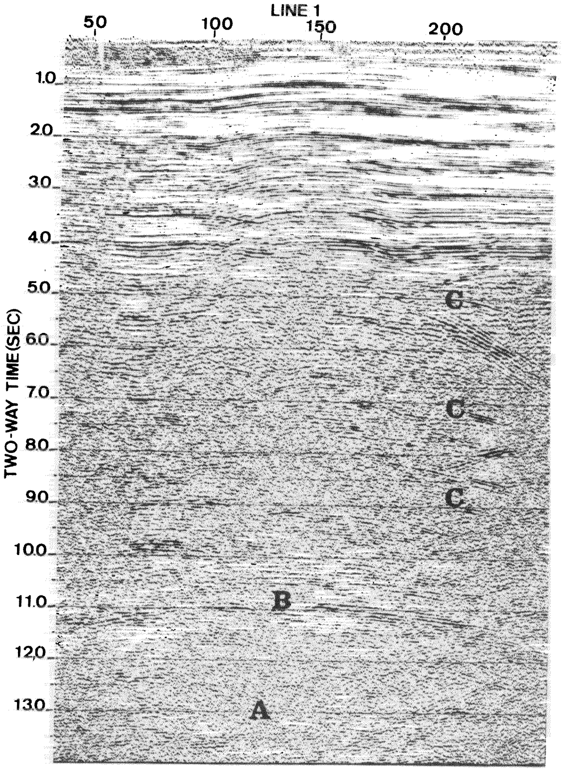

Fig. 8. Reflection profile showing the deep part of line 1. Good reflections to 14 s (A) may include much multiple-reflection energy. Anticline in strong reflection at 11.0 s. (B) occurs beneath the Pacific Creek anticline in the sedimentary rocks and may be caused by multiple reflections. Dipping events on right side of section (C) may be reflections arriving from outside the plane of the section.

(Figures 8 and 9). The anticline is cut on its west flank by a thrust fault along which it grew. The thrust dies out high in the sedimentary section and may predate the Wind River thrust so that thrusting progressed from west to east.

A regular dip of 10°-15° off the northeast flank of the Wind River uplift appears in the reflections on the east side of line 1A and the west side of line 2 (Figures 7 and 12). Depth of basement ranges from 1 s on the west to 2.5 s in the center of line 2. On the east side of the line, three major faulted anticlines are crossed; these structures are producing oil fields so that data quality deteriorated because of local noise generated.

Precambrian crust. Crustal reflections are best analyzed from line 1A (stations 100-125), where Precambrian rocks crop out; numerous crustal reflections appear in fine data unspoiled by multiples. A fascinating pattern of reflections emerges to give a representation of Precambrian crustal structure never before observed. Generally, extensive reflections in the upper crust are not very common. Many short reflections and one long reflection dipping northeast are scattered throughout the upper crust (Figures 6, 13, and 14). Surface exposures contain gneisses and schists that should act as reflectors, but their tight folding and steep dips [Bayley et al., 1973] probably degrade reflections except for short segments from favorably oriented layers. The middle crustal zone from 4 to 6 s shows few reflections, and then in the deep crust a spectacular zone of irregular diffuse reflections appears (Figures 6, 14, and 15). In the southwestern part of the section a broad complex reflection pattern exhibits a characteristic signature. Some reflections are horizontal, and many short reflections dip steeply to the southwest. These terminate toward the Wind River thrust, but their migrated position may well be on the hanging wall of the thrust. A detailed interpretation of these complex structures awaits successful migration of the time section; as this moves reflection segments into their true position, this will compress anticlines and bring out synclines. At these depths and velocities, lateral movement during migration may be extreme.

We may infer some aspects of this complex structure (Figures 14 and 15) that occurs at a depth of about 20 km. The number of reflections shows that many layers may be involved in the structure, which is probably synformal. Greater curvature with depth suggests that these events cannot be diffractions, and the tight structure suggests a synform [Fitch, 1976]. In the deeply eroded core of the Wind River Mountains, large pyroxene granulite (gabbro) layers are interfolded isoclinally with granitic gneisses in a high-grade metamorphic complex [Perry, 1965]. This unique structure on line 1A could represent the seismic response of gabbroic layers in a complex fold structure [Smithson et al., 1977]. If this is the case, then the rocks are probably isoclinally folded, and the upright fold seen in the seismic section represents a later open folding of the layering.

A similar structure appears across the thrust at about 6 s (Figures 6, 14, and 15). While the geometry is not exactly the same, we again see repetition of reflections and layering together with interfering reflections, indicative of need for migration even with the gentler dips. We correlate this structure with the one 2 s deeper across the fault zone. These reflection patterns and variable dips are the reflection seismic response of complex deep crustal structures that could resemble features mapped in deep exposures of the crust and that have never before been resolved at this scale by deep reflection profiling. These complicated irregular reflection patterns that would probably become more coherent with migration are exactly what we would expect if the lower crust resembles exposed basement rock.

Interpretation of deep crustal reflections is less straightforward on lines 1 and 2 because multiples generated in the overlying sedimentary section make recognition of crustal reflections more difficult. Nevertheless, a number of crustal reflections have been picked where criteria such as dip and character allowed them to be reasonably distinguished. On these lines the number of crustal reflections picked is relatively small and may represent a highly biased sample. Figures 8 and 16 show good reflections in the deep part of line 1. The band of reflections at 11 s may come from a layered deep crustal reflector, or it may be a multiple. The

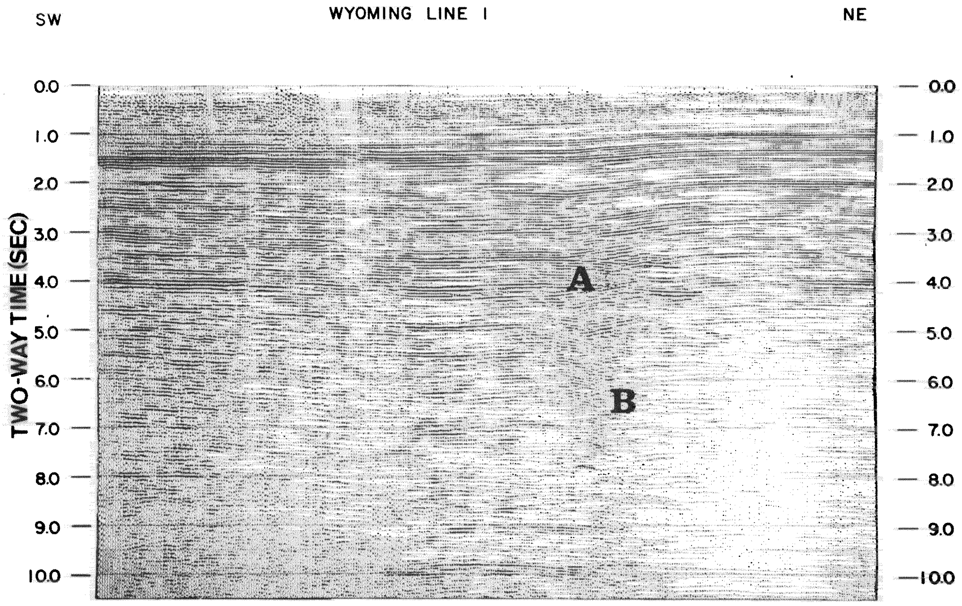

Fig. 9. Near-trace stacked section for line 1. About 3:1 horizontal exaggeration. Because multiple-reflection cancellation is achieved in the more distant traces, the near-trace stack enhances multiples. Note the strength of the horizontal reflections down to 10 s. Characteristic bow tie effect from the syncline with a buried focus (A, 3-4 s) clearly repeats from 5 to 7 s (B); this is well below the base of the sedimentary section and must therefore be a multiple reflection.

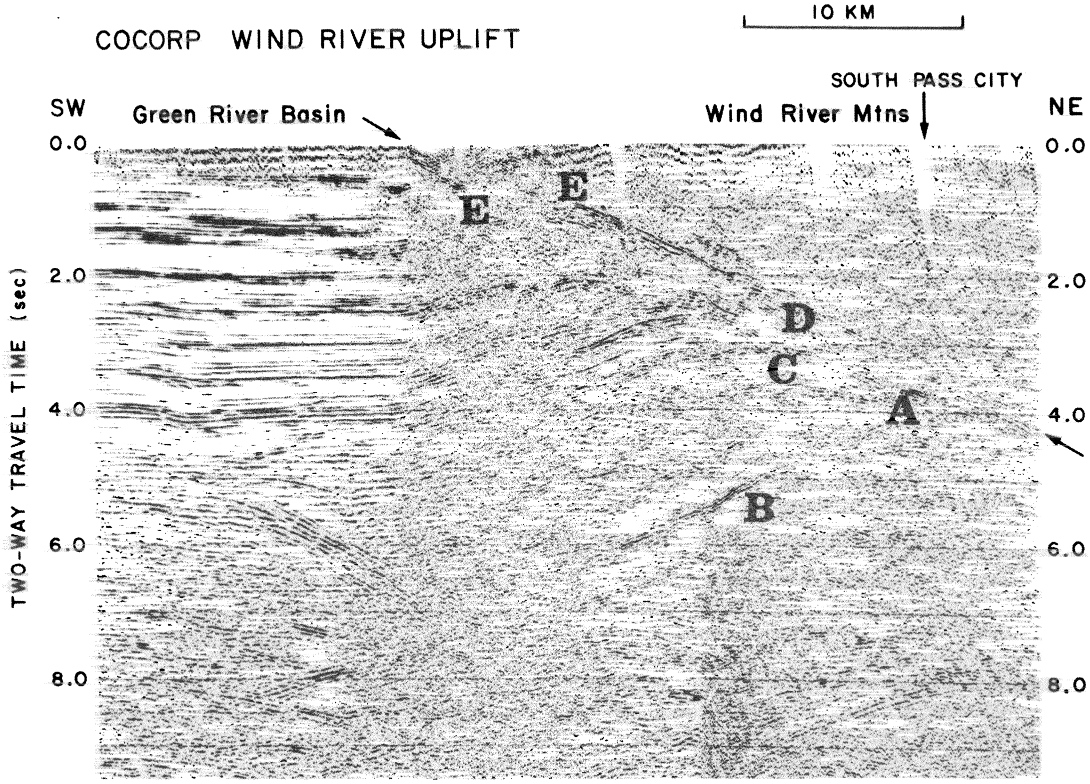

Fig. 10. Close-up of lines 1 and 1A across the thrust (arrows). Deepest faulted sedimentary rocks (A). Dipping events (B, 5-6 s) may be an anomalous reflection associated with the Wind River thrust. Probable folding in sedimentary rocks against the fault (C). Fault reflection and possible overturned beds (D). Thrust apparently flattens near the surface (E, 0.6-0.9 s).

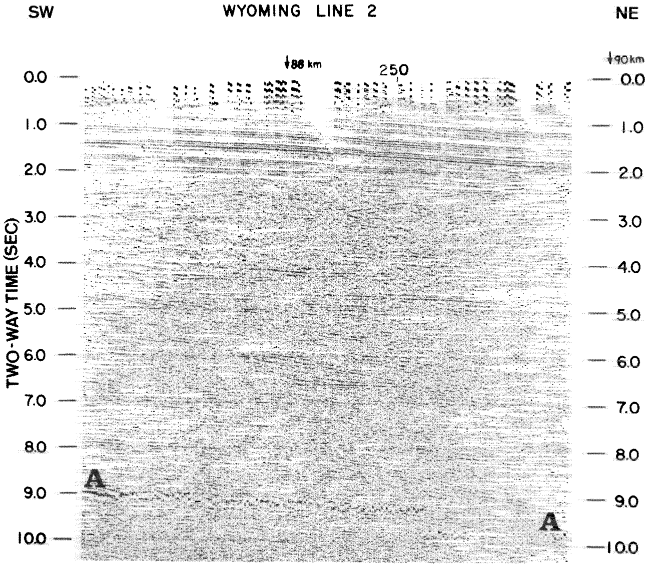

Fig. 11. Close-up of anomalous low-frequency event on line 2 (A, 9.0-10.0). This could be an unusual deep reflection, but because of its high move-out shown in CDP gathers and its low frequency it is probably not a reflection.

multicyclic character similar to sedimentary reflections and the anticlinal structure suggest that this is a multiple reflection because this anticlinal feature is located beneath the Pacific Creek anticline. This coincidence between shallow and deep structures, which is more striking on a migrated section, hardly seems to be pure chance. On the other hand, the reflection of 15 s seems to be a primary reflection and may come from the Moho. This corresponds to a depth of about 45 km, which would be an appropriate depth for the Moho but somewhat deeper than 40 km determined from an unreversed refraction profile by Braile et al. [1974].

The Wind River thrust. The shallow position of the Wind River thrust has been commonly mapped in industry seismic reflection profiles [Berg, 1962] because the overhang of Precambrian crystalline rocks against underlying sedimentary rocks provides a major contrast in acoustic impedance. The same is true for this Cocorp profile in which the thrust can be clearly recognized in the first 3.9 s (Figures 10 and 17). Repetition of reflections parallel to the thrust may be caused by sedimentary rocks overturned and pulled into the thrust plane. The thrust appears as a fairly continuous simple reflection from 1.0 to 2.0 s and can be followed upward to a point on the surface coincident with the buried trace of the Wind River thrust marked on the geologic maps [Zeller and Stephens, 1964]. Below 2.0 s the reflection event marking the thrust splits into two major subparallel zones distinguished by continuous reflections. These can be followed continuously to about 3.9 s depth, the approximate base of the sedimentary section in the Green River Basin. Surprisingly, the fault reflection does not end here. The same set of reflections can be traced from the near surface where they are known to mark the thrust to a time of 7.0 s and possibly further. Because this set of reflections is continuous from where where it is known to mark the thrust, we correlate the deep reflections to a depth of 7.0-8.6 s in the crust with the Wind River thrust. In contrast to the reflection-seismic recognition of most faults which is based on loss of data [Kelsey, 1949], in this study the position of the fault is determined directly as discrete reflections.

The apparent dip of reflection events is uniform at 30°-35° to 6.2 s. From 6.2 to 8.7 s the reflections split further into possibly three zones, with different dip and character (Figure 14). Faint evidence exists for continuing the fault to 9.5 s. The fault might continue further, but any such continuation of the fault is obscured by a decrease in data quality and by possible multiple reflections on the west side of line 2 (Figure 7). The Wind River thrust is thus a most profound feature in the crust and can be traced to a true depth of about 24 km and possibly deeper.

Evidence for more than one period of movement is furnished by a split of the thrust into two parts between the surface and 1.0 s. A very shallowly dipping portion (15°-20°) can be followed to the surface, and a more steeply dipping branch (30°) can be traced to a position near the surface about 2.4 km to the northeast (Figures 13 and 17). Similar divergence of the thrust planes occurs at 2.0 s and possibly deeper. First movements may have created an irregular thrust zone. Later movements along this initial zone of deformation were along a more planar thrust zone.

A hand-migrated section (Figure 17) has been prepared in order to minimize distortion caused by velocity and changes in line direction. This shows the apparent dip of the fault steepening to a maximum of 38° and possibly shallowing at depth.

At the top of the Precambrian basement, minimum horizontal movement of 26 km (measured from the position of the thrust at the surface to the point at which it cuts the base of the sedimentary rocks) has taken place along the thrust. This corresponds to at least 13 km of vertical uplift along the thrust plane).

The Wind River thrust parallels the Continental fault near its tip (Figure 17), a normal fault that may be listric with 0.4 km of downthrow to the north. Movement occurred during Late Tertiary uplift of the area [Zeller and Stephens, 1964] and may represent the mass of upthrust Precambrian settling into the sedimentary rock under its own weight [Sales, 1968].

Typical criteria for faulting in seismic reflection sections is loss of reflections near the fault, but in striking contrast, the Wind River thrust is clearly seen on Cocorp reflection profiles deep into the earth's crust, a fact that indicates an adequate contrast in acoustic impedance across the fault or between the fault zone and surrounding rock. This contrast generating reflections must be caused by a mylonitized zone of rock along the fault or by juxtaposition of different rock types across the fault. When we consider the great movement on the thrust, both of the above possibilities

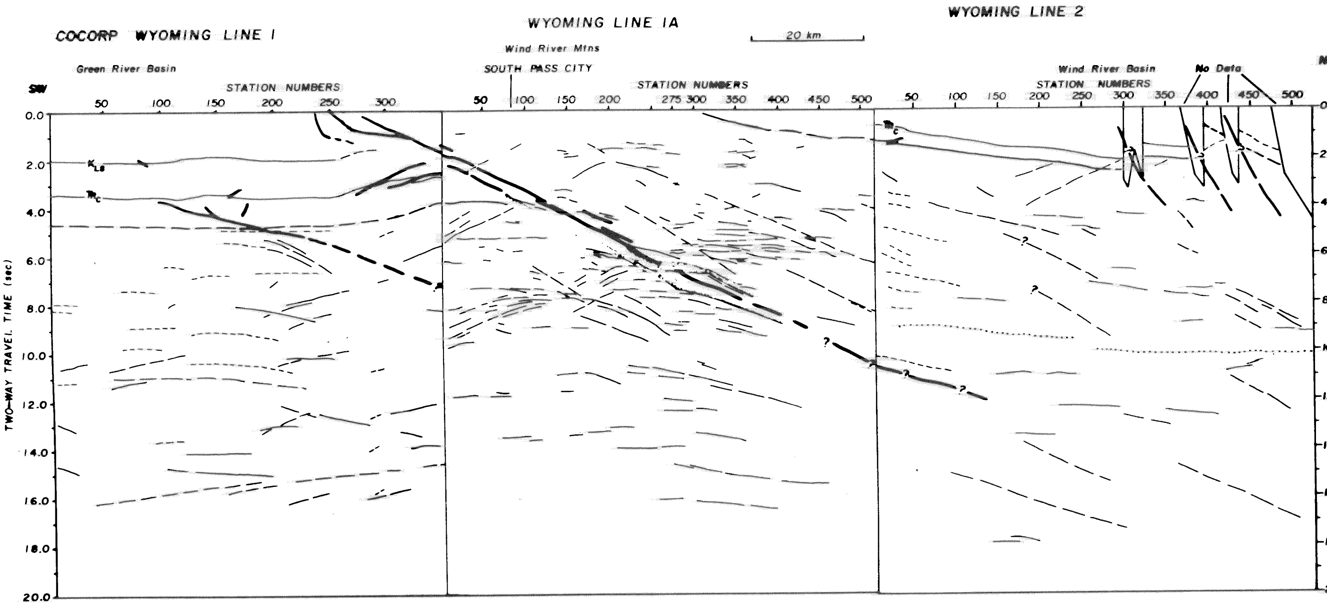

Fig. 12. Line drawing composite showing the structure and reflections picked for lines 1, 1A, and 2. Continuation of thrust below 9 s is highly questionable.

seem to be plausible explanations for fault reflections.

Other weaker events of dip similar to the Wind River thrust reflection appear on lines 1A and 2 (Figures 6 and 7). Many of the dipping events on line 2 are caused by multiple reflections which obscure primary events. These other dipping events do not cut the sedimentary section and cannot be shown to be thrusts by offsets along individual beds. Although a number of reflections appear in the middle and lower crust, individual reflection horizons are not distinct enough to be correlated across any of these dipping events.

The mass of Precambrian basement thrust over sedimentary rocks in the Green River Basin caused intense deformation just under the thrust. The base of the sediments can only be poorly picked in the seismic data, but it appears to have remained relatively undeformed. The seismic sections (Figures 10, 13, and 17) show uplift of sedimentary rocks under the thrust. This uplift is mostly velocity uplift caused by the effect of high-velocity material above the thrust. Ray paths in this complex structure make structural interpretations uncertain, but some structural uplift may be present. Note (Figure 13) that reflections from the base of the sedimentary section flatten near the fault and appear to roll over into the fault; this observation indicates some structural dip to the northeast or that the velocity contrast has disappeared in the deepest part of the sedimentary section. Local depressing of basement into the fault is probable (Figure 17).

The sediments under the thrust are cut by several conjugate thrust faults of dip opposite to the main thrust, where several reflections show the faulting well (Figure 13). Sense of deformation in sedimentary rocks under the thrust has been clockwise opposite to the direction of movement along the thrust. Folding of sedimentary rocks against the thrust is not visible in the seismic data. Sharp folding into the thrust probably would not be resolved. Several events that parallel the main thrust (Figure 13) may be caused by thrust slices of sedimentary rocks pulled into the thrust plane [Berg, 1962].

Conclusions about the deep movement of the fault may be obtained from correlation of deep reflection patterns on line 1A. Reflections between 6 and 10 s in the middle of line 1A (Figure 14) are so distinctive with respect to this and other deep crustal sections [Oliver et al., 1976; Oliver and Kaufman, 1976] that we prefer to correlate them across the Wind River thrust. Even though these reflection patterns differ in detail, we believe they represent the same structure that has been offset along the fault. This correlation with a vertical offset of 1-2 s implies that 3-6 km of vertical offset or 6-12 km of movement is still present along the fault at 24-km depth.

Gravity Interpretation

The large positive gravity anomalies associated with Laramide uplifts in Wyoming [Berg and Romberg, 1966; Case and Keefer, 1966; Malahoff and Moberly, 1968; Karasa and Smithson, 1977] show that mass excess in the crust results from Laramide flanking faults. For this reason a gravity survey was conducted over the southern part of the Wind River Mountains. About 900 gravity measurements were completed during the summers of 1977 and 1978, including some using horses for transportation in the nearly inaccessible Precambrian core of the mountains. Gravity measurements were reduced to obtain simple Bouger gravity anomalies by standard techniques [Dobrin, 1976]. These Bouguer gravity values form the basis for a gravity profile from Farson to Riverton about 10 km north of the seismic profile (Figure 4). This gravity profile is slightly north of the gravity profile previously computed

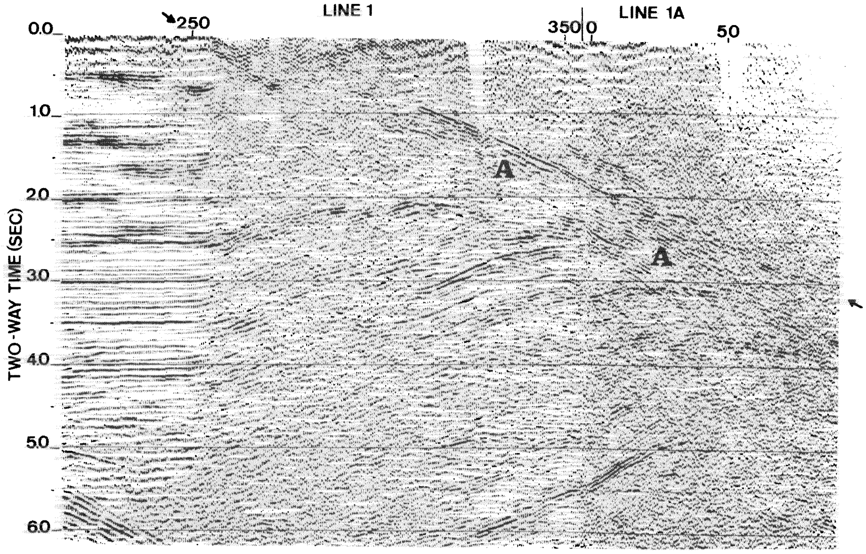

Fig. 13. Close-up of lines 1 and 1A showing details of Wind River thrust (compare with Figure 10). Data quality decreases abruptly at station 250, where the thrust approaches the surface. Multiple cycles in the reflection band marking the thrust (arrows) may be caused by sedimentary layers dragged into the thrust plane and by subsidiary thrusts (A).

[Smithson et al., 1978] in order to avoid local complexities in the anomalies caused by Precambrian iron formation. Bouguer anomalies range from -250 mGal in the Green River Basin to a maximum of -163 mGal in the Precambrian core of the uplift and back down to -220 mGal in the Wind River Basin. The gravity profile is asymmetrical, with a higher gradient near the Wind River thrust than on the northeast flank of the uplift.

Free air gravity anomalies range from +100 to 200 mGal in areas of flat topography over the uplift and are near zero in the adjacent basins. The free air anomaly gives an estimate of isostatic compensation and shows that the uplift is undercompensated; i.e. abnormally dense material is located beneath the Wind River uplift. The uplift is probably too narrow to be compensated isostatically.

Density of sedimentary rocks has been determined from formation density logs and ranges from 2.2 to 2.65 g/cm^3. Density is strongly dependent on depth as well as rock type [Malahoff and Moberly, 1968], so that densities of the same formation are greater in the Green River Basin than in the Wind River Basin. Unfortunately, no wells penetrate the entire sedimentary section in the Green River Basin, so densities from lower Mesozoic and Paleozoic rocks are not directly available from this basin. Densities of Precambrian rock range from 2.65 to 3.10 g/cm^3. Mean density

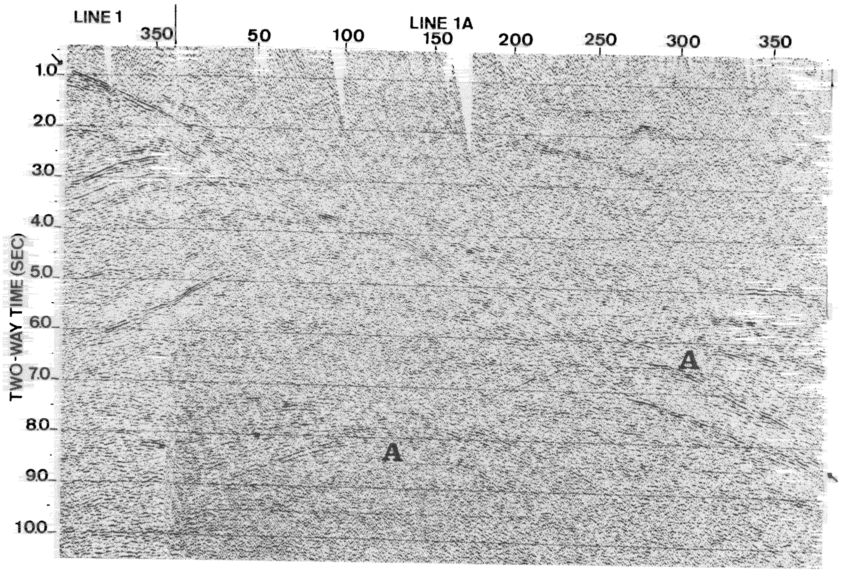

Fig. 14. Close-up of profile from line 1A showing the fault (arrows) and complex structure (A) in the deep part of the section. Numerous deep crustal reflections that show a folded structure.

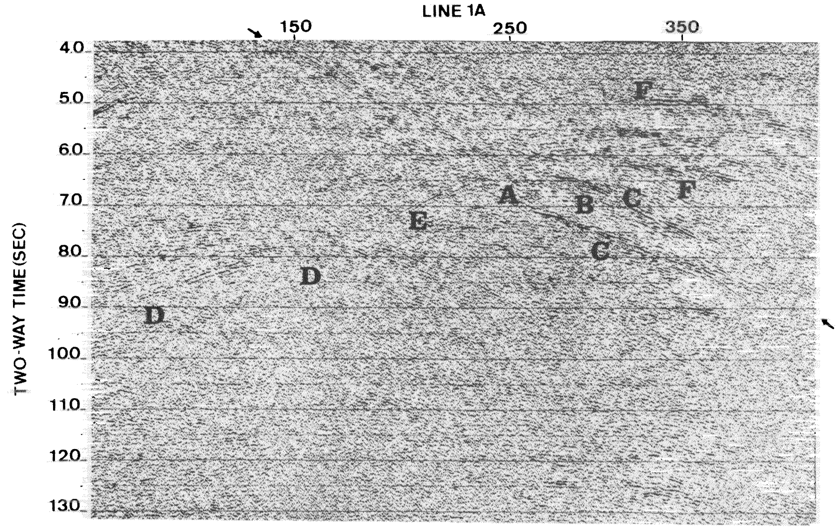

Fig. 15. Close-up of profile from line 1A showing the fault (arrows) in the deepest part of the sections and the complex crustal structure near the fault. Fault may branch (A at 6.5 s), but preferred interpretation is that fault (B) passes between layered rock units (C). Note convex structure in weak interfering reflections (D at 8 s), events with high SW dip (E at 6.5-7.0 s), and complex structure with stronger reflections above the fault (F at 5.0-6.5 s). Numerous layers are present in both these structures, which appear to be folded. Note the striking contrast in character between these deep reflections and the deep reflections on lines 1 and 2, where many of the deep reflections are likely multiples from within the overlying sedimentary rocks.

of granitic rocks from the central Wind River Mountains is 2.7 g/cm^3 [Smithson and Ebens, 1971]. A mean density of 2.73 g/cm^3 is used for the Precambrian based on measured rock densities.

The major feature of the gravity profile is the large increase in gravity over the Precambrian core of the uplift, which is well substantiated from earlier studies. Most of the earlier gravity interpretations of Laramide uplifts did not include deep crustal structure in their models; i.e., only the gravity effect of basement rocks against sedimentary basins was modeled. Much but not all of this increase over the Wind River uplift 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 therefore be caused by some deeper source which is also causing part of the undercompensation. This deeper source is logically associated with faulting, so that the position of the fault from the seismic section fixes the geometry of the uplifted mass excess.

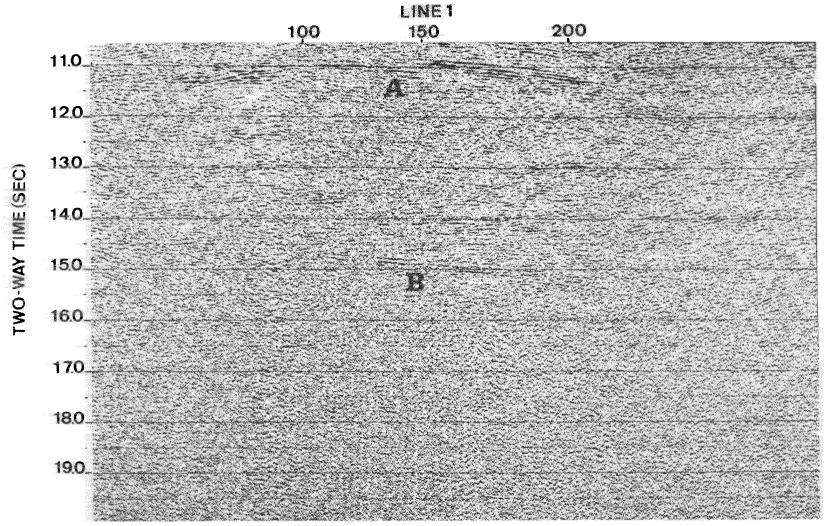

Fig. 16. Close-up showing the deepest part of line 1. Stronger event in upper part of the section may be a multiple reflection (A). The clear reflection at 15 s (B) may be a primary reflection because of its different character and dip and because it is at the apropriate depth (about 45 km) for the Moho.

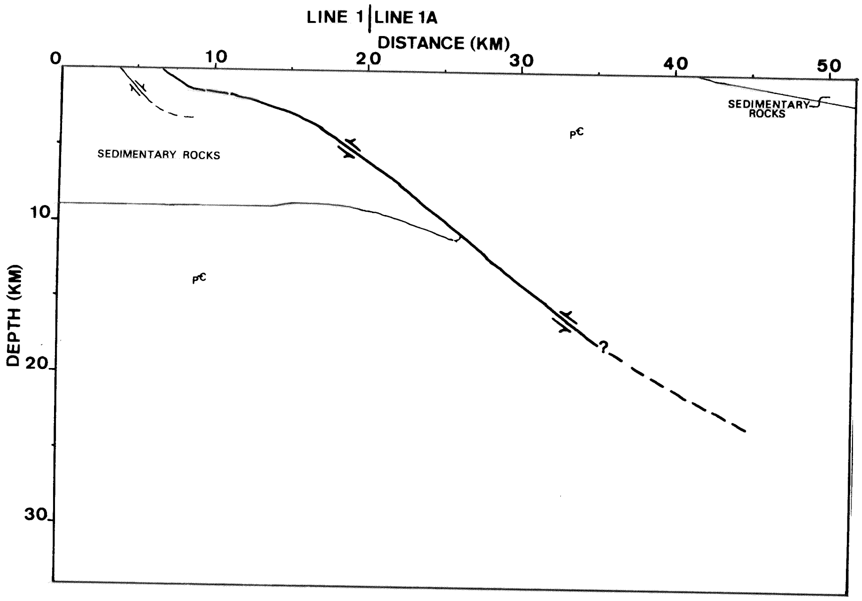

Fig. 17. Migrated position of Wind River thrust projected into a plane that parallels the seismic line. Migration by hand using a velocity function varying from 5.8 km/s at the surface to 6.2 km/s at 8 s. Maximum apparent dip is 38°; true dip based on strike determination from gravity contours may be up to about 48°.

Bouguer gravity anomalies have been modeled using geological control, the seismic section for basin geometry, which is relatively well determined, and the seismic interpretation for geometry at depth. After accounting for the gravity effect of low-density sedimentary rocks against Precambrian basement the additional positive anomaly might be caused by uplift of more dense lower crust and/or uplift of upper mantle material along the fault. Both possibilities have been modeled, but the observed profile can best be fit by the gravity effect of uplifted lower crust (Figure 18). If the effect of uplifted mantle is modeled, its gravity effect is too broad and 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 seismic interpretation.

Several important conclusions may be drawn from the gravity interpretations. Dense material must be upfaulted or intruded underneath the uplift. The gravity model based on more dense lower crustal material offset along the fault (i.e., 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 subsequently been equalized by creep.

Conclusions

Cocorp deep crustal reflection profiles have provided data that are decisive for interpretation of Laramide foreland structure in the Wind River uplift of the Wyoming province. The fault acts as a reflector through most of the crust and can be clearly traced to a depth of at least 24 km, with an apparent dip of 30°-38°. Fault reflections within the crystalline crust are probably generated from different rocks juxtaposed along the fault, from a mylonite zone along the fault, or from both. We chose to correlate structures at a depth of about 20 km across the fault; this interpretation suggests that up to 6 km of vertical separation may still be present at this depth. The Wind River uplift started to form as a large fold, and, as movement progressed, deformation continued as faulting; the upper crust acted as a rigid slab and the lower crust flowed. Style of deformation ranges between that in Figure 1c and Figure 1e. For this uplift the question of vertical versus horizontal movements is resolved.

The Wind River thrust appears as a shear fracture caused by crustal compression extending through most of the crust. Horizontal movements predominate, and vertical movement may be ruled out as the primary cause of the Wind River uplift. Crustal shortening occurred; this compression and resulting shortening can be related to plate movements during the Laramide orogeny [Brewer et al., 1979].

Gravity interpretation nicely complements the seismic interpretation because the seismic interpretation provides constraints and because the gravity field shows structure that is not presently interpretable from the seismic data. The gravity field can be modeled using the fault geometry from the reflection interpretation as a constraint. This modeling shows that most of the large Bouguer gravity anomaly is caused by the effect of Precambrian crust against low-density sedimentary rocks of the basins but that dense material must also have been emplaced at depth beneath the uplift. This dense material must be displaced to the northeast of the axis of the uplift and could involve uplift of dense lower-crustal material or the mantle but not both on

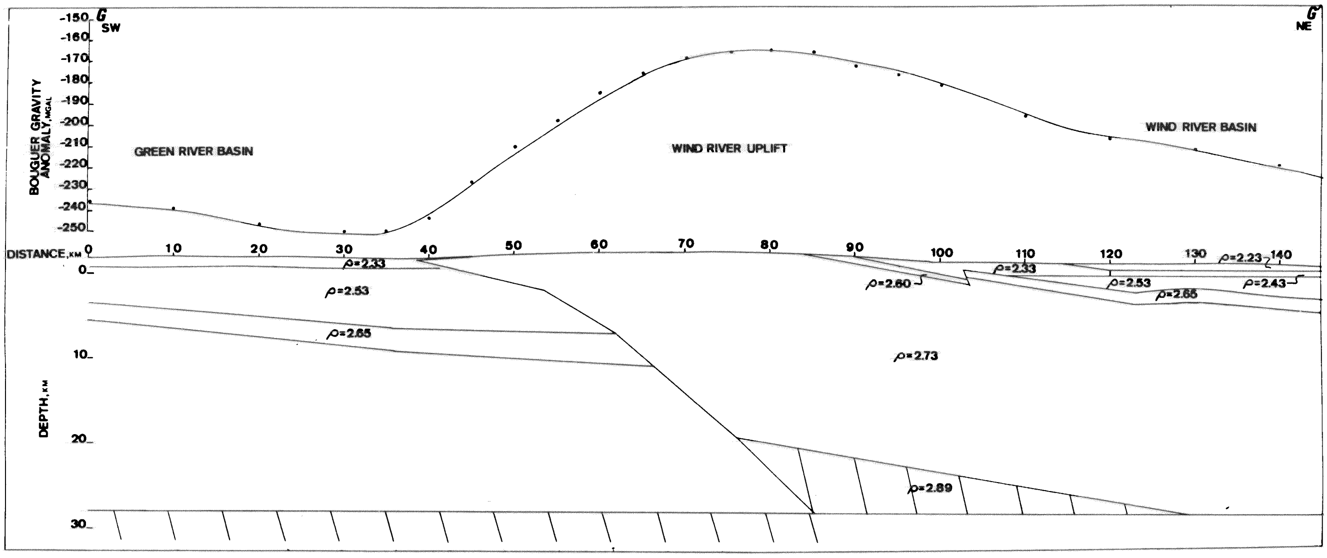

Fig. 18. Bouguer gravity anomalies and calculated model along profile G-G' in Figure 4. Horizontal and vertical scale in kilometers. Parameter ρ is density in grams per cubic centimeter. Continuous line represents observed gravity, and dots represent modeled gravity.

the basis of plausible density contrasts. This dense material could well be included in the complex crustal structure between 6 and 8 s along the fault (Figures 14 and 15). The shift of the gravity maximum to the northeast probably excludes vertical faulting or crustal basaltic intrusion [Eardley, 1963] as the primary cause of the uplift. The gravity interpretation suggests but does not prove that no appreciable displacement is present in the Moho. If we are correct about the 6 km of vertical separation at 20 km, the faulting has probably not died out before it reached the Moho. Either the thrust decreased in dip to parallel the Moho, or the Moho was offset during Laramide deformation but has since flowed by creep to a constant level.

The Moho does not appear as a strong or continuous event in the reflection data. Either the Moho has low reflectivity for near-vertical incidence seismic waves, or energy input was too low. Our present inferences about the Moho offset come from gravity data, and the reliability of these inferences depends on how well we have been able to account for gravity effects of sedimentary rocks.

Much of the reflection energy on lines 1 and 2 appears to be generated by multiple reflections. If so, multiple reflections may be more common in deep crustal reflection data than has previously been recognized and represent a danger to deep crustal reflection interpretation. The striking contrast in reflection character between lines 1 and 2 and line 1A where the Precambrian is exposed sharply illustrates the advantage of working where crystalline crust is at the surface.

Complex crustal structure unlike any other previously found has been resolved on line 1A. This structure is suggestive of many layers that have been complexly deformed and comes closer to seismic reflection resolution of typical Precambrian structures than anything previously found in the deep crust. This feature stands in sharp contrast with the short, near-horizontal or moderately dipping reflection segments commonly found in earlier crustal reflection studies and represents the most interesting crustal structure found by reflection seismology other than the Wind River fault itself.

The fascinating deep structure appearing between 6 and 8 s ($\sim$20 km) on line 1A (Figure 15) is the first complex structure resolved by crustal reflection profiling. It is probably a multiply deformed structure of a complexity typical of structures found in exposed basement rocks and as such may represent how the seismic signature of the deep crust should look. The ultimate goal of future crustal reflection studies will be to migrate such reflection patterns into an image, obtain physical properties of the reflectors, and interpret the geological significance of the feature. The ability to resolve such potentially complex features is present in crustal reflection data.

Besides the attitude and magnitude of the Wind River thrust, the most surprising aspect of this study is the ability of seismic reflection profiling 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, where an adequate contrast in acoustic impedance exists across the fault. By locating faults and monitoring physical properties along faults, crustal reflection interpretation may be a major aid to earthquake prediction and hazard research. Reflection studies will be capable of yielding important new information on deep crustal structure associated with suture zones. The ability to resolve thrusting in crustal sections formed from ancient island arcs and crustal thickening by interthrusting of slabs at deep crustal levels and underplating will have exciting implications for crustal genesis.

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