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THE LARAMIDE OROGENY: EVIDENCE FROM COCORP DEEP CRUSTAL SEISMIC PROFILES IN THE WIND RIVER MOUNTAINS, WYOMING

J.A. BREWER, S.B. SMITHSON *, J.E. OLIVER, S. KAUFMAN and L.D. BROWN

Department of Geological Sciences, Cornell University, Ithaca, N.Y. 14853 (U.S.A.)

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ABSTRACT

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Deep crustal reflection data that are critical for the interpretation of Laramide structure have been obtained by the Consortium for Continental Reflection Profiling (COCORP). The Laramide orogeny, which occurred from the late Cretaceous to early Eocene, is characterized in Wyoming by large uplifts of Precambrian basement, commonly flanked by reverse faults. The attitude of these faults at depth has been a major tectonic problem and is very important for deciding whether horizontal or vertical crustal movements were primarily responsible for the basement uplifts. COCORP has run 158 km of deep seismic reflection profiles (recording to 20-sec two-way travel time) across the southeastern end of the Wind River Mountains, the largest of these Laramide uplifts. Reflections from the thrust fault flanking the Wind River uplift can be clearly traced on the profiles to at least 24-km depth and possibly as deep as about 36 km with a fairly uniform apparent dip of 30°—35°. Other reflection events subparallel to the main Wind River thrust are present in the seismic profiles and may represent other faults. There is at least 21 km of crustal shortening along the thrust. There is no evidence in the reflection profiles for large-scale folding of the basement; the Wind River Mountains were formed predominantly by thrust movements. Gravity anomalies in the Wind River Mountains can be modeled by a thrust that displaces dense material in the lower crust. If the thrust ever cut the Moho, the effect is not observed in the gravity today. A proposed model for the presence of uplifted basement in Wyoming invokes a shallowly dipping, subducted Farallon plate beneath the North American continent; drag between the two plates localized compressional stresses in an area over 800 km into the North American plate causing large thrusts to develop. The earth's crust seems to have fractured as a fairly rigid plate.

INTRODUCTION

The origin of the distinctive basement uplifts that occurred in the Cordilleran foreland during the Laramide orogeny has been a major tectonic

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* This research was done while on sabbatic leave at Cornell University. Now at Department of Geology, University of Wyoming, Laramie, Wyo. 82070 (U.S.A.).

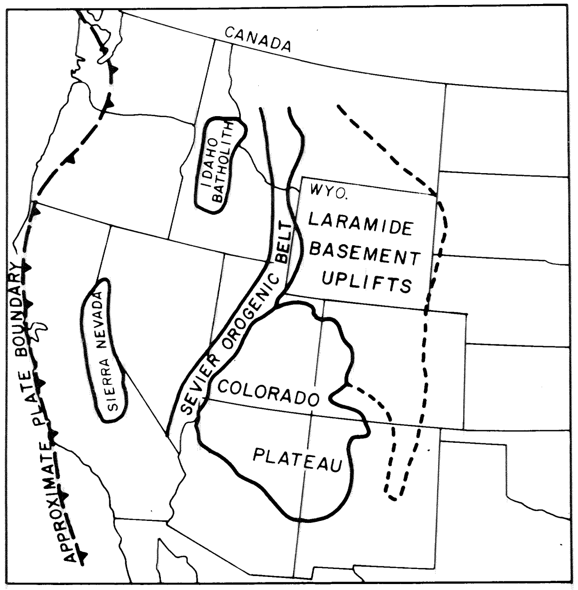

Fig. 1. Area of Laramide basement uplifts in the western United States. The approximate position of the North American plate margin during the Laramide orogeny differs from the present because of late Cenozoic extension in the Basin and Range province, mainly in Nevada.

problem. Whether deformation was due to vertical, horizontal, or strike slip movements of the earth's crust is much discussed in the literature (e.g., Berg, 1962, 1963; Blackstone, 1963; Eardley, 1963; Pricha et al., 1965; Sales, 1968; Stone, 1969; Stearns, 1971, 1975; Lowell, 1974; Couples, 1977). In an attempt to resolve this problem the Consortium for Continental Reflection Profiling (COCORP) has carried out deep crustal seismic reflection profiling across the largest of these uplifts, the Wind River Mountains in Wyoming. The seismic profiles clearly show that this uplift was formed by movement along the Wind River thrust, a major thrust that extends deep into the crust with an apparent dip of 30°—35°. The geometry of the thrust indicates that the Wind River uplift was the result of horizontal compression of the earth's crust (Smithson et al., 1978, 1979).

The Laramide orogeny can be traced from Alaska to northwestern South America. Its initiation at about 80 m.y. B.P. and its cessation at about 40 m.y. B.P. have been correlated with the separation of North America from Europe (Coney, 1972). The most intense deformation occurred in the Cordilleran foreland in Wyoming and Colorado 60—55 m.y. B.P. (Berg, 1962) resulting in large rectilinear basement uplifts of a very distinct structural style, often flanked by faults. Deformation in the Cordilleran geosyncline to the west of the foreland occurred during the late Mesozoic Sevier orogeny (Fig. 1) (e.g., Armstrong, 1968). Deformation is characterized by

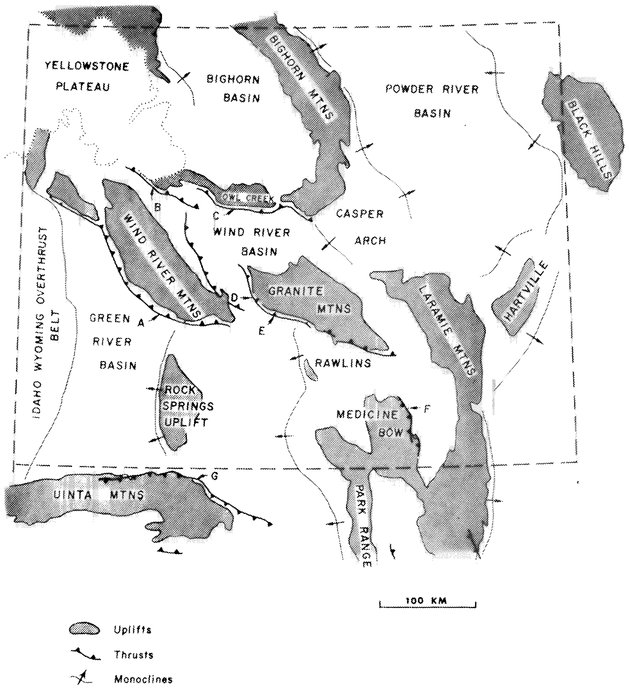

Fig. 2. Tectonic map of Wyoming showing diversity of Laramide trends. Thrusts are: *A* = Wind River thrust; *B* = EA thrust; *C* = Owl Creek thrust; *D* = Immigrant Trail thrust; *E* = Sheep Creek thrust; *F* = Medicine Bow thrust; *G* = Uinta Mountains thrust. (After Berg, 1962.)

thin-skinned tectonics of the Idaho—Wyoming thrust belt. Long sinuous folding of beds and low-angle thrust faulting verge to the east (e.g., Armstrong and Oriel, 1965). Thrusting started in the western part of the belt in the late Jurassic and ended in the eastern part in the early Eocene. The Sevier orogenic belt lies to the east of a Mesozoic volcanic—plutonic arc, and is related to the convergence between the North American plate and an oceanic plate (Burchfiel and Davis, 1975).

The Laramide basement uplifts of Wyoming occurred 800—1000 km east of the North American plate margin (Burchfiel and Davis, 1975, 1976) and up to 400 km east of the Idaho—Wyoming thrust belt (Lowell, 1974). These uplifts do not fit into standard plate tectonic orogenic types (arc orogens, collision orogens, or transform orogens; Dickinson and Snyder, 1978). The region lacks orogenic features typical of these types, e.g., a volcanic front, flysch-type sedimentation, a suture structure, or major transcurrent faulting.

The Laramide basement uplifts of Wyoming have been a major problem to explain in a plate tectonic framework (Fig. 2). The recognition of the

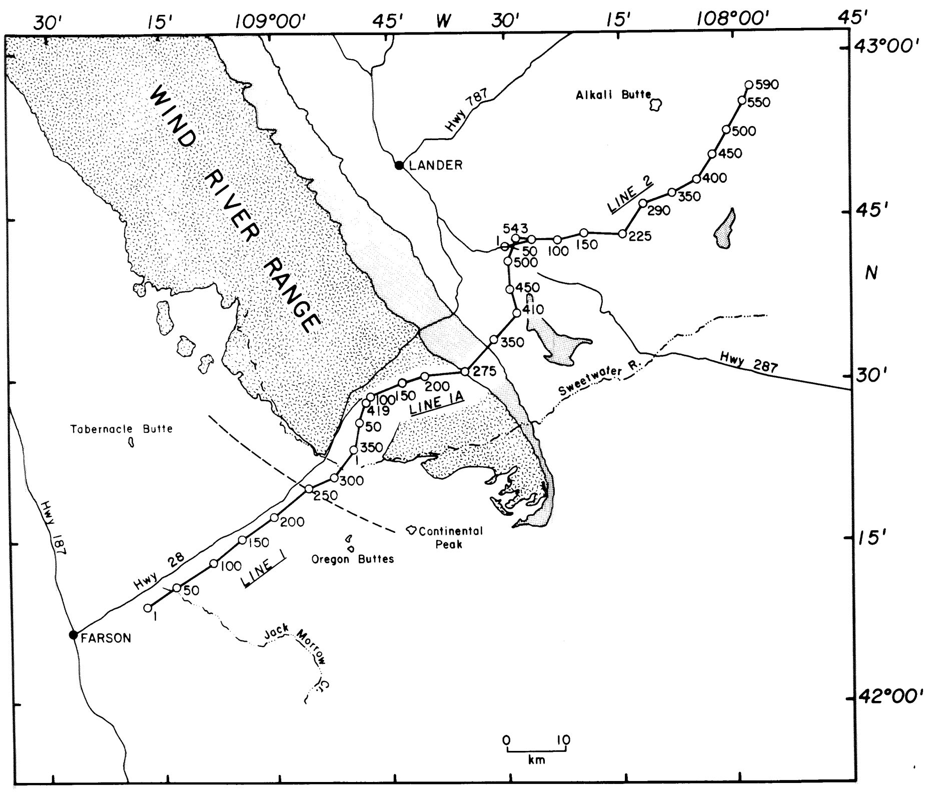

Fig. 3. Location map for COCORP lines *1*, *1A* and *2*. Numbers on the lines are vibrator stations. Precambrian rocks are coarsely stippled; Paleozoic sediments are finely stippled. The Wind River thrust crosses line *1* at about station 250.

predominant type of deformation producing the uplifts enables much better control to be placed on possible plate tectonic models for the area, and is extremely important for understanding how the Rocky Mountains were formed. A major constraint on the type of deformation is provided by a knowledge of the attitude at depth of faults flanking the basement uplifts. Deep crustal seismic reflection profiling is the only geophysical technique of sufficient resolution to determine this.

This paper describes in detail the attitude and character of the Wind River thrust seen on COCORP deep reflection data, and disusses regional tectonic implications, Smithson et al. (1978) have briefly presented the major results of this COCORP work, and a detailed description of the data seen on the reflection profiles and the data processing techniques used is in preparation (Smithson et al., 1979).

THE RATIONALE FOR COCORP DEEP CRUSTAL SEISMIC REFLECTION PROFILING

The successful application of VIBROSEIS® * techniques for collecting deep data has been described by Fowler and Waters (1975), Oliver and Kaufman (1976), Oliver et al. (1976), and Mair and Lyons (1976). Reflection events from deep within the earth's crust and possibly upper mantle have been recorded using this method. Deep crustal seismic reflection profiling had previously been carried out by COCORP in the Rio Grande rift, New Mexico and Hardeman County, Texas. In all areas data were recorded to depths of at least 40 km.

The Wind River uplift in Wyoming was chosen as a site by COCORP because of the importance and well-defined nature of the geological problem, the attitude of the Wind River thrust at depth. Shallow seismic reflection profiles recorded by industry and well control showed that in the shallow sedimentary section the Wind River thrust was well-defined with a dip of about 20° (Berg, 1962, 1963). Previous seismic reflection results of Junger (1951) near the Wyoming border and of Perkins and Phinney (1971) in the Wind River area indicated the presence of deep crustal reflections.

FIELD TECHNIQUES USED TO COLLECT COCORP DEEP CRUSTAL SEISMIC DATA

Three continuous reflection profiles (recorded to 20-sec two-way travel time) were run by COCORP. The South Pass area of the Wind River Mountains (Fig. 3) was chosen for logistical considerations. Line *1* (52.2 km long) was run in the fall of 1976 through the Green River basin south of South Pass City in the Wind River Mountains. Line *1A* (53.6 km long) was run as an extension of this in the fall of 1977 from South Pass City, east and north into the Wind River basin, and line *2* (52.3 km long) was run in the fall of 1977 east and north to end in the middle of the Wind River basin. Field techniques used were similar to those described by Oliver et al. (1976) and Oliver and Kaufman (1976). Seismic data in the form of 24-fold common-depth-point reflection profiles were collected by Petty-Ray Geophysical Company under contract to COCORP using the VIBROSEIS® technique. In 1976 a 48-channel digital recording system was used with station intervals of 134 m, and a spread of 6.4 km. In 1977 a 96-channel digital recording system was used with station intervals of 100 m and a spread length of 9.6 km. The source array consisted of five synchronously operated vibrators stationed in line. Each vibrator moved through sixteen stages per station so the field record per station consisted of 80 summed vibrator sweeps. As the source array moved continuously along the line, sufficient data were collected to produce a 24-fold common-depth-point stack in the final

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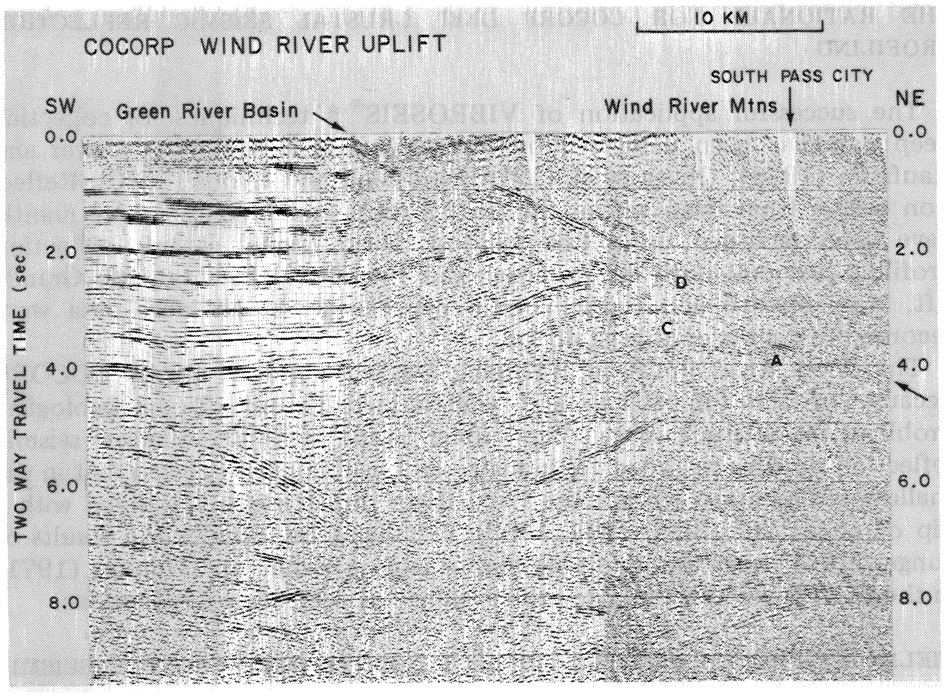

Fig. 4. Unmigrated seismic section showing the upper part of the Wind River thrust (marked by arrows). *A* = Point at which base of sediments is cut off by the thrust; *C* = apparent arching of the sediments under the thrust; *D* = depth at which the thrust splits into two zones.

processing. The vibrator pilot signal was an 8—32 Hz linear upsweep. In 1976 the length of the sweep was 20 sec, but in 1977, in order to put more energy into the ground, a sweep length of 30 sec was used. Listening time was 50 sec in both cases so that after correlation the record length was 30 sec in 1976 and 20 sec in 1977 (one second two-way travel time approximately equals 3 km depth). The seismic sections (Figs. 4 and 5) and the diagram showing the major events seen on the three lines (Fig. 6) are unmigrated and represent data in time rather than in depth.

SUMMARY OF THE GEOLOGY OF THE WYOMING AREA OF BASEMENT UPLIFTS

During the Paleozoic and most of the Mesozoic, Wyoming was part of the Cordilleran foreland (Keefer, 1970). Sedimentary rocks from all systems except the Silurian were deposited in repeated transgressions of the sea, and little major tectonic activity occurred (Keefer and Van Lieu, 1966; Keefer, 1970). Laramide deformation in Wyoming started in the late Cretaceous, in post-Lewis, pre-Lance times (Love, 1954). Major downwarping of the Precambrian basement in the areas now marked by sedimentary basins (e.g., the Wind River and Green River basins) occurred with upwarping of surrounding areas. Movements culminated in intensity in the early Eocene with the formation of Precambrian basement highs along major thrust and reverse faults. Basement uplifts practically ceased to grow at the end of the Eocene. For the remainder of the Tertiary the structural basins thus formed were filled with clastic debris from the surrounding basement highs, and the whole area was nearly base-leveled by the end of the Oligocene (Shaw, 1970). At the end of the Tertiary the entire region was elevated over 1500 m to start the present cycle of erosion, and minor normal faulting caused partial collapse of some of the Laramide uplifts (Keefer, 1970).

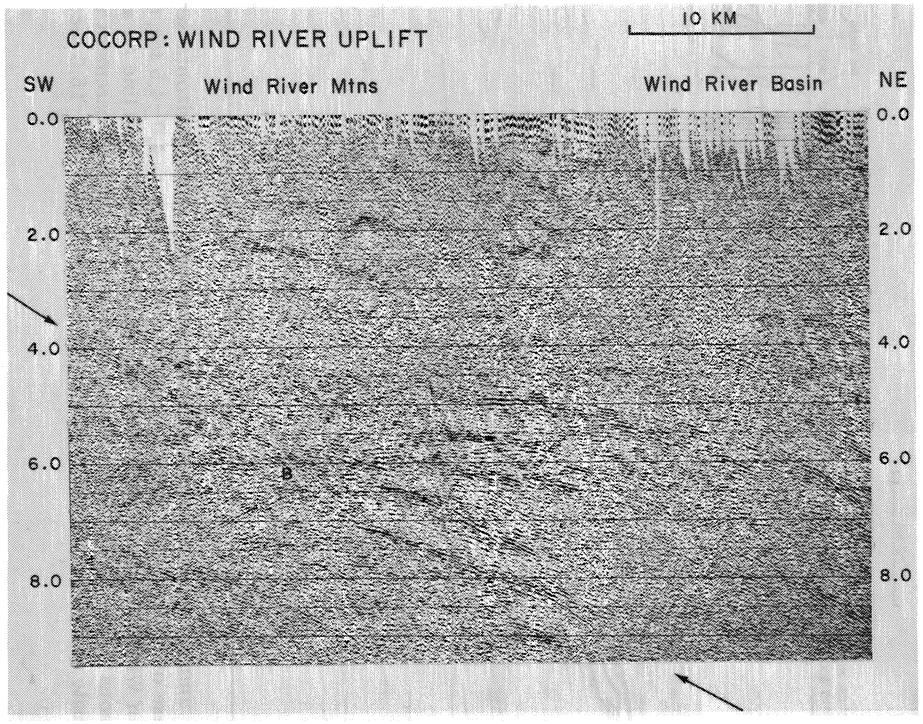

Fig. 5. Unmigrated seismic section showing the Wind River thrust in the lower crust. (Thrust is marked by arrows.) *B* = Region in which thrust splits into possibly three sections in lower crust.

Many of the structural basins and uplifts formed during the Laramide orogeny are asymmetrical in cross section. The uplifts have three distinct structural trends; northwest—southeast, north—south, and east—west (Blackstone, 1963) (Fig. 2) and are often flanked by reverse faults. The amount of relief on the Precambrian basement surface created by Laramide deformation is enormous. The Precambrian surface in the Wind River Mountains is over 4.3 km above sea level and in the Green River basin is over 8.2 km

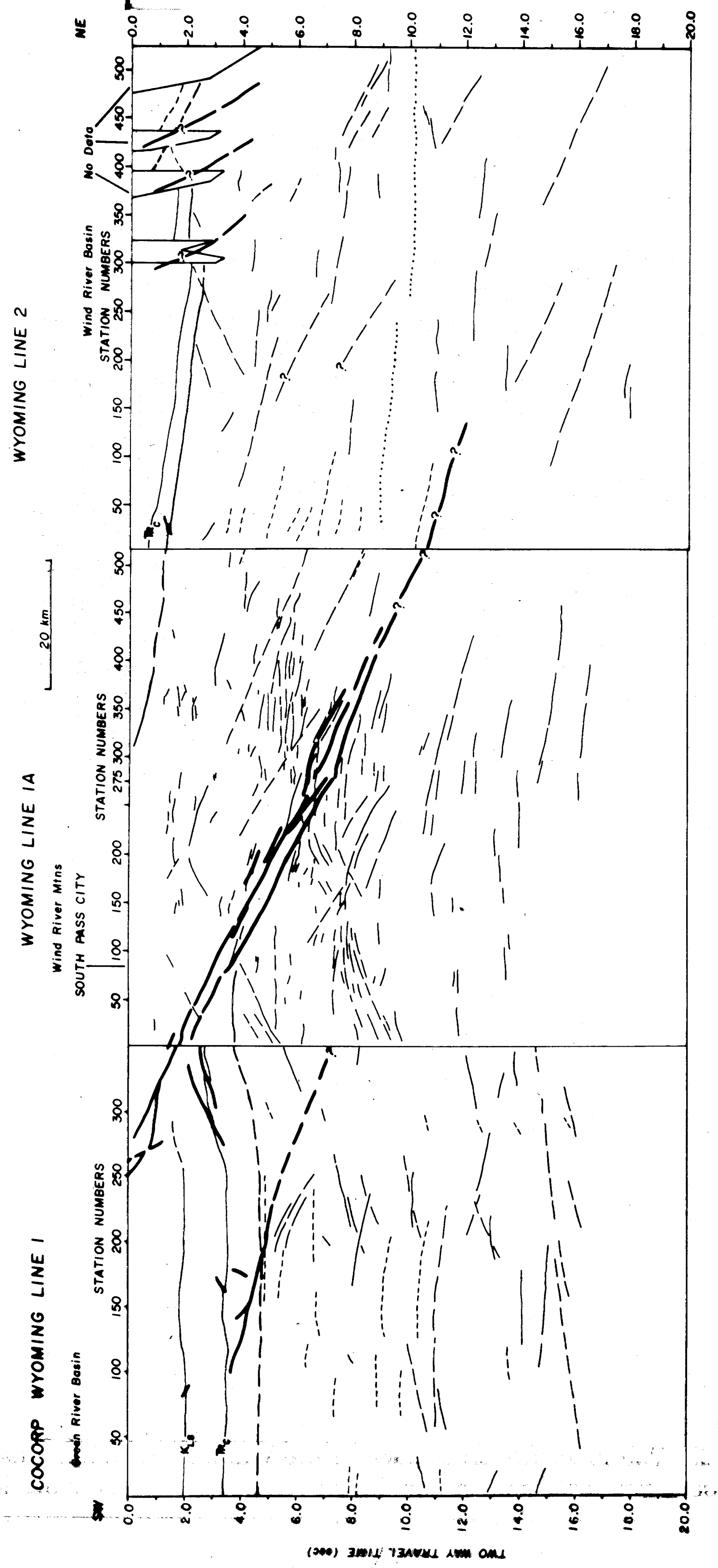

Fig. 6. Main features of COCORP lines *1*, *1A* and *2*. Sections are unmigrated and vertical scale approximately equals horizontal scale except in sediment section. Thrusts and faults are heavy lines. Base of Green River basin sediments is dashed line at 4.0—4.5 sec, cut off by Wind River thrust under South Pass City on line *1A*. Base of Wind River basin sediments appears at Station 275 on line *1A* and dips to N.E. Tr_C = Triassic Chugwater Formation; K_{LS} = Cretaceous Lewis Shale. Short dashed lines in Precambrian basement are possible multiples. Many events in the lower and middle crust indicate complex structure. Possible Moho reflector at 14.0—15.0 sec on line *1*. Dotted line on line *2* is an enigmatic low-frequency event.

below sea level, representing about 12.5 km vertical offset (Berg, 1962). Similar figures obtain for displacement between the Bighorn Mountains and Bighorn basin (Stearns, 1975). Thick Tertiary basinal sequences have accumulated, indicating that the Precambrian basement moved both up and down during the Laramide orogeny (Sales, 1968; Stearns, 1971, 1975); downward movements were at least as great as upward movements (Sales, 1968).

The Wind River uplift is the largest uplift of Precambrian basement rocks in Wyoming. It is a northwest—southeast trending anticlinal structure about 220 km long and 70 km wide (Fig. 2). The Precambrian core of the uplift consists of deep crustal migmatitic rocks. Granitic intrusions and supracrustal rocks of higher crustal levels are found in the southeastern part of the uplift. These rocks constitute some of the oldest Precambrian crust in the U.S., and are dated at 2.7 m.y. B.P. (Naylor et al., 1970). The southwest flank is underlain by the Wind River thrust, which is obscured in the south of the range by overlapping Eocene sediments (Zeller and Stephens, 1964a, b, 1969). The COCORP seismic lines ran over exposed Precambrian in South Pass, mainly meta-greywacke but also meta-andesites and meta-conglomerates (Bayley, 1965; Bayley et al., 1973). It has been suggested that these rocks represent an Archaen greenstone belt (Condie, 1972). Paleozoic and Mesozoic strata dip gently off the northeast flank of the uplift at 12°—15° (Keefer, 1970) into the Wind River basin.

CHARACTER OF THE WIND RIVER THRUST SEEN ON COCORP SEISMIC REFLECTION PROFILES

The Wind River thrust can be followed as a continuous series of reflection events from the surface, where the reflections are known to represent the thrust, deep into the lower crust. It can be clearly distinguished in the upper four seconds of the seismic records where Precambrian rocks are carried over Green River basin sedimentary rocks (Fig. 4). The thrust appears as a fairly continuous simple reflection event from 1.0 to 2.0 s and can be followed upwards to a point on the surface coincident with the buried trace of the Wind River thrust marked on geological maps of the area (Zeller and Stephens, 1964b). At about 2.0 s (Fig. 4, *D*) the reflection event marking the thrust splits into two sub-parallel zones distinguished by continuous to semicontinuous reflection events with minor sub-parallel discontinuous zones of reflections. These can be followed continuously to about 3.9-s depth, the base of the sedimentary section of the Green River basin, and farther down to 6.2-s depth through the middle crust (41 km horizontally from the surface expression of the thrust). The apparent dip of these reflection events to 6.2 s is remarkably uniform at about 30° (Figs. 4, 5).

From about 6.2 to 8.5 s the reflection events further split into possibly three zones, and the apparent dip decreases to about 25°. Two of these zones have a higher amplitude reflection than is seen elsewhere along the thrust.

Possibly they may represent lithological discontinuities rather than the thrust surface itself (Smithson et al., 1979). This change in apparent dip coincides with a change in line direction between stations 250—275 of line *1A* (Fig. 6). Weak evidence exists for continuing the reflection events down to about 12 s on line *2* (Fig. 6; a horizontal distance of almost 70 km from the surface expression of the thrust). In this part of the record, the seismic lines were crossing the layered sedimentary rocks of the Wind River basin. At depth many events are seen with a similar dip to the sedimentary layering, some of which may be multiples. Primary events might be expected to dip in a similar direction because of movements along the fault, and it is difficult to separate primary events from possible multiply reflected events.

The seismic lines change direction several times. These changes were used to obtain a rough estimate of the true dip and dip direction of the fault by the method of Telford et al. (1976). The fault dips northeasterly at between 30° and 35° down to about 6 s. Below this the dip appears to increase to about 41°, in a more easterly direction. If the weak evidence for continuing the fault to 12 s is accepted, the dip is about 38° but changes to a more northeasterly direction at this depth. These figures are very rough estimates because it is not easy to define the exact position of the fault plane at depth, and because some of the line changes are not pronounced.

The thrust plane appears to split into two parts above 1.0 s (*G* in Fig. 7): (1) a very shallowly dipping portion (15°—20°) that can be followed to the surface, and (2) a more steeply dipping (about 30°) portion that can be traced to a position near the surface about 2.4 km to the northeast. Similar divergence of the thrust planes occurs at about 2.0 s and possibly deeper (Fig. 4). Near the surface the planes are crosscutting. This geometry may have been produced by one or more periods of movement during the Laramide orogeny. Another possibility is that a much older fault plane or weakness existed along which Laramide thrusting occurred.

At the top of the Precambrian basement, there was a minimum horizontal movement along the thrust of 21 km (measured from the position of the thrust at the surface to the point at which it cuts the base of the Green River basin sediments). This represents at least 14 km of vertical uplift along the thrust plane.

The Wind River thrust is cut by the Continental fault near its tip (*F* in Fig. 7), a normal fault with 0.4 km of downthrow to the north, active in the late Tertiary uplift of the area (Zeller and Stephens, 1969). It probably represents the mass of upthrust Precambrian settling under its own weight into the sediments below (Sales, 1968).

Seismic reflection profiles from sedimentary sections usually show a loss of reflections in the vicinity of faults (Kelsey, 1949). The Wind River thrust is very clearly seen on the COCORP seismic reflection profiles deep into the earth's crust, indicating an adequate impedance contrast. This impedance contrast could occur if the fault were a thick zone of sheared or mylonitized rock, or if the fault juxtaposed rocks of sufficiently different physical properties. Considering the great movement on the thrust, a mylonite zone of different acoustic impedance and juxtaposition of different rock types across the fault are both plausible explanations for the fault reflections (Smithson et al., 1979).

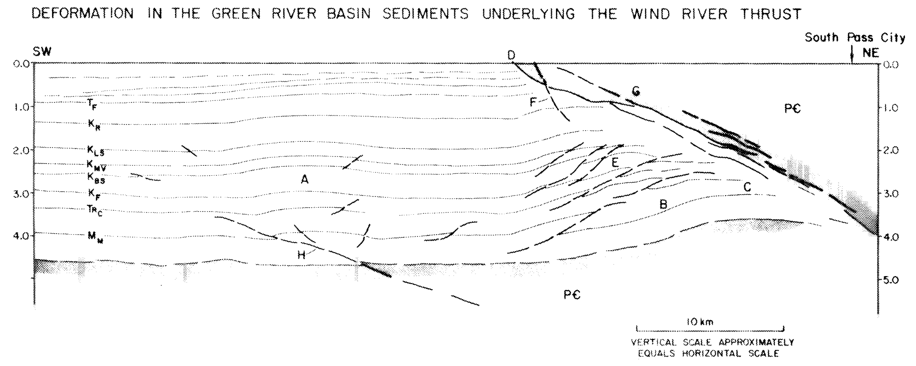

Fig. 7. Deformation in the Green River basin sediments underlying the Wind River thrust. Section is unmigrated and vertical scale approximately equals horizontal. T_F = Tertiary Fort Union; K_L = Cretaceous Lance; K_{LS} = Cretaceous Lewis Shale; K_F = Cretaceous Frontier; K_{MV} = Cretaceous Mesaverde; K_{BS} = Cretaceous Baxter; Tr_C = Triassic Chugwater: M_M = Mississipian Madison. Cretaceous and Tertiary formations picked from well logs, lower formations are inferred. *A* = Pacific Creek anticline; *B* = apparent uplift of sediments under thrust; *C* = apparent flattening of sediments close to thrust; *D* = position of Wind River thrust at surface; *E* = reverse thrust faults; *F* = Continental fault; *G* = crosscutting relations seen along Wind River thrust; *H* = small thrust underlying Pacific Creek anticline.

The geometry of the Wind River thrust is a very strong indication that crustal shortening occurred through horizontally rather than vertically directed forces.

EVIDENCE FOR OTHER THRUSTS IN THE SEISMIC REFLECTION PROFILES

Other, weaker events with a similar dip to the Wind River thrust reflection appear on the seismic sections (Fig. 6). The most southwesterly of these offsets the Madison limestone in the Pacific Creek anticline but does not offset the Chugwater formation (*H* in Fig. 7). It can be followed as a weak event into the Precambrian basement with an apparent dip of approximately 10° to the northeast to about 5.5 s and possibly deeper. On a migrated profile this event is seen to offset the sedimentary section near the base, representing another thrust, though only with a very small amount of movement along it.

Other weak events with a similar dip to the Wind River thrust event can be seen on lines *1A* and *2* (Fig. 6). However, some of the dipping reflected energy seen in this area might be due to multiples generated in the sedimentary section which could 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. There is much structure in the middle and lower crust, but individual reflecting horizons are not distinct enough to be correlated across these events.

There is inferential evidence for the existence of other thrusts in the crust overlying the Wind River thrust. Fig. 6 shows the geometry of the Wind River thrust and the sediments on the southwestern edge of the Wind River basin (which dip about 10°—15°). The base of these sediments was probably approximately flat (similar to the Green River basin) before upthrusting occurred. By considering the geometry that would be produced by reversing the movements along the Wind River thrust, a certain amount of clockwise rotation is seen in the crust upthrust along the Wind River thrust. This clockwise rotation may have been produced by additional material brought into the crust between the Wind River thrust and the sediments of the Wind River basin by movement along thrust faults to the northeast of, and structurally above, the Wind River thrust. Subsidence of the Wind River basin after thrusting may also have produced the clockwise rotation.

DEFORMATION IN THE GREEN RIVER BASIN SEDIMENTS

Well logs were used to correlate the Tertiary and Cretaceous sedimentary units of the Green River Basin; the lower units were inferred.

Thrusting of the mass of Precambrian rocks caused thinning and intense deformation in the sedimentary wedge under the thrust. The base of the sediments cannot be picked well on the seismic profiles, and its position is largely inferred. It appears, though, to have remained relatively underformed.

The seismic sections (Fig. 4) show uplift of the sediments under the thrust. Most of this uplift is "pull-up" due to the presence of the relatively high-velocity Precambrian rocks above. However, examination of Fig. 4 shows that the reflections from beds near the base of the sedimentary section flatten close to the thrust, indicating some structural dip to the northeast. Average velocities to the Madison limestone were obtained during the processing of the seismic data. Because of the geometrical assumptions inherent in the technique, these velocities are very suspect under the thrust, but if they are assumed correct, then a maximum of about 1 km of structural uplift (*C* in Fig. 7) has occurred on the Madison limestone just under the thrust. Complex wave paths through the thrust surface confuse interpretation in this area.

The sediments under the thrust are cut by several conjugate thrust faults of opposite dip to the main thrust (Fig. 4, *E* in Fig. 7). The Cretaceous Baxter formation and Mississippian Madison limestone are good reflectors that show this type of faulting well. These "reverse faults" probably do not cut the Precambrian basement. The sense of deformation in the sediments under the thrust has been clockwise, in opposition to the direction of movement along the main thrust. Similar "back thrusts" have been described in overthrust sheets of the central Appalachians (Bick, 1973; Perry, 1978).

The Madison limestone and the top of the basement can be seen on the seismic sections close to the fault itself (Fig. 4) and show no evidence of overturning along the fault in response to thrust movements. Data from an American Quasar well that penetrates through the overthrust Precambrian into the underlying sedimentary rocks show overturning of the sediments along the thrust. Overturning may be too tight to be seen in seismic reflection profiles. Higher in the section very few coherent events can be picked under the fault. Although several events lie subparallel to the main thrust (Fig. 4), they may represent thrust slices of sediments or Precambrian rocks along a fairly wide fault zone, or overturned sedimentary bedding.

To the southwest of the thrust, deformation in the sediments dies out rapidly into the Green River basin. Small high-angle reverse faults occur, but the major feature is the Pacific Creek anticline (*A* in Fig. 7). Sediments deposited during thrust movements thicken to the northeast and overlie folded sediments of the Pacific Creek anticline. Upwarping therefore appears here before the Wind River thrust event. As discussed above, the anticline is cut near its base by a minor thrust penetrating the basement (*H* in Fig. 7).

HISTORY OF THE WIND RIVER UPLIFT

Deformation started with minor upwarping of the basement and sediments in the region now under the Wind River thrust and in the Pacific Creek anticline. As compressive stresses built up (by mechanisms to be discussed later) fracturing of the basement occurred, first of all under the Pacific Creek anticline since this feature precedes the main thrust episode. Main fracturing in this area occurred along the Wind River thrust plane. The thrust movements sheared the base of the sedimentary section apparently in a brittle fashion. We see no evidence for drag folding along the thrust, but possibly fold hinges would be too tight to appear on seismic reflection profiles. The thrust formed along the northeast limb of the previously formed upwarp referred to above. There was at least 21 km of horizontal movement along the thrust and 14 km of vertical movement.

Reverse thrust faults formed in the sedimentary section under the thrust in response to clockwise deformation induced in the competent Paleozoic rocks. As the Wind River thrust continued to override the sediments these reverse thrusts were rotated anticlockwise to their present positions. Bedding plane faults or local detachment surfaces must have been formed near the base of the sedimentary section to accommodate these movements. Thinning of the sediments also occurred, probably by movement along bedding plane thrusts that die out in the Green River basin and which do not show on the seismic reflection profiles. From the complex nature of the thrust zone discussed above, probably more than one phase of movement occurred on the Wind River thrust. Movements may also have occurred on other, minor thrusts to the northeast to account for the dip of the sediments in the Wind River basin, and on the extensions of the Emigrant Trail thrust. These are not seen on the seismic reflection profiles because of noise generated by producing oil fields in this part of the Wind River basin. They have been marked on the section from geological maps of the area (Keefer, 1970) (Fig. 6).

Final movements on the Wind River thrust occurred in the early Eocene (Keefer, 1970). The final deformation event seen in the seismic profiles is the normal faulting on the Continental fault. The last movements occurred along the fault in the post mid-Pliocene (Love, 1954).

IMPLICATIONS FOR LARAMIDE DEFORMATION

The moderate apparent dip (30°—35°) and the great depth of the Wind River thrust strongly indicate that the Wind River Mountains were produced by horizontally rather than vertically directed tectonic forces (see discussions by Berg, 1962, 1963; Blackstone, 1963; Eardley, 1963; Prucha et al., 1965; Stearns, 1971, 1975; and Couples, 1977).

The COCORP seismic reflection profiles strongly indicate that the basement has behaved rigidly during the Laramide deformation. There is no evidence of major folding, but low amplitude arching of the basement either prior to, or in response to, the main thrust movements may have occurred just under the Wind River thrust plane and under the Pacific Creek anticline. These two features are minor, and the latter is fault-bounded also. Tight overturning of the sediments under the thrust surface occurred. The basement in the Green River basin is approximately horizontal, and the dip of the basement into the Wind River basin is fairly uniform at 10°—15°. This suggests that the crust as a whole has flexed upward along the thrusts as a fairly rigid body. Rigid here implies a crust with sufficient internal strength to fracture without large-scale folding. It appears not to have deformed plastically on a large scale, yet also probably did not deform elastically.

Hafner (1951) modeled the stress distribution on a homogeneous, isotropic elastic slab subjected to horizontally directed pressure (Fig. 8). In his model two conjugate sets of fault planes were formed, at an angle of about 32° above and below the horizontal, and this is similar to the observed apparent dip angle on the Wind River thrust (30°—35°). Stearns (1975) has questioned whether Hafner's (1951) modeled stress system should be applied to combined basement and sedimentary sections (where the sediments are layered, anisotropic and inhomogeneous). The Wind River thrust does not change its attitude significantly from the basement into the sedimentary rocks, so the stress distriburion between the two was probably not markedly different.

It is not appropriate to model an elastic block at the elevated temperatures and pressures found deep in the crust. Instead, the crust there tends to deform plastically. Borg and Handin (1966) conducted laboratory experi-

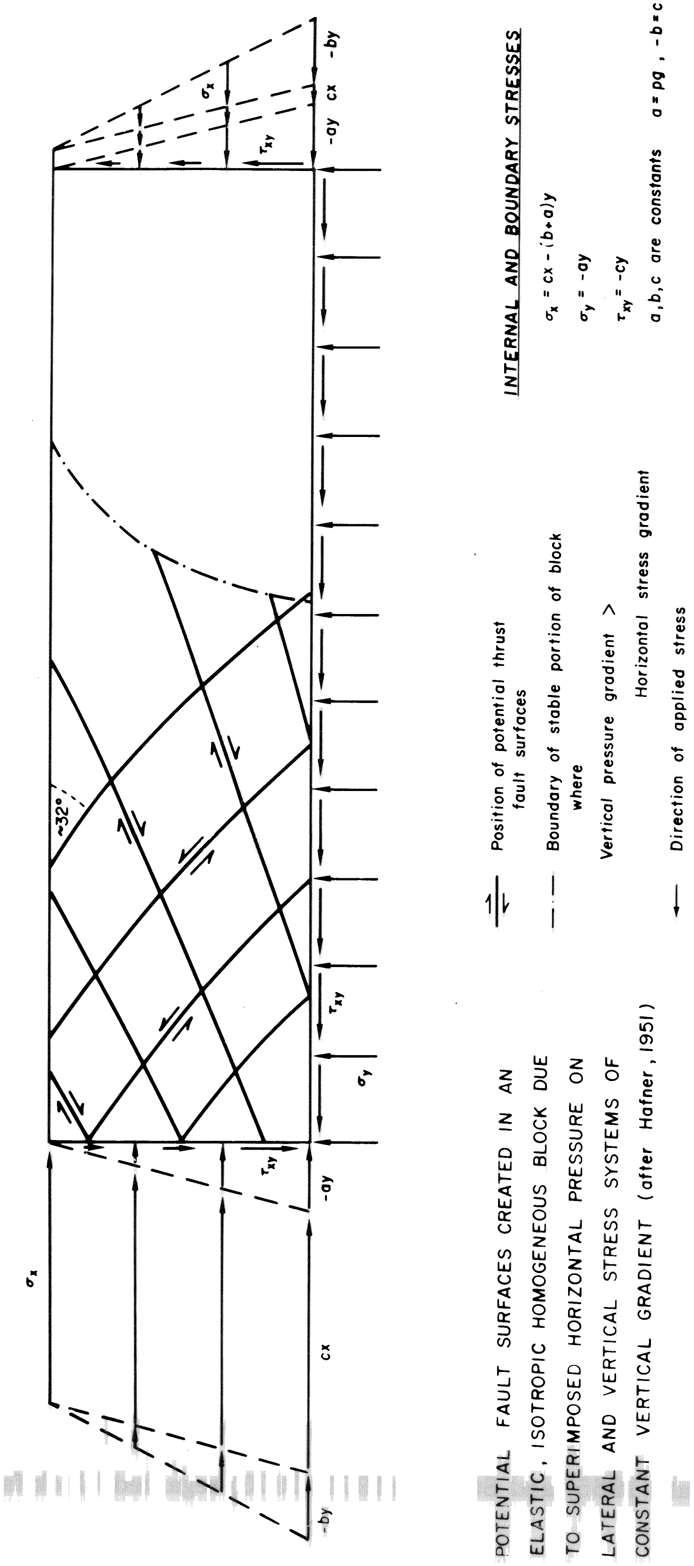

Fig. 8. Position of potential fault surfaces in elastic block (after Hafner, 1951).

ments on typical basement rocks at high strain rates (1% min^{-1}) which suggested that brittle fracturing occurs down to 17-km depth. Heard (1962) found similar results for more geological reasonable strain rates. The upper part of the faulting system may reasonably be modeled as a brittle fracture of elastic crust. A possible lower limit for brittle behavior is at depths corresponding to about 3 kbars (D.L. Kohlstedt, personal communication, 1978), or about 10-km depth. This is only about 1 km deeper than the Green River basin so that most of the brittle part of the crust is occupied by sedimentary rocks. Possibly Hafner's (1951) modeled stress distributions are valid for sedimentary rocks to a first approximation.

Post (1977) documents ductile faulting in dunite samples deformed under confining pressures of 5—15 kbars and temperatures of 700—1350°C. The orientation of the shear zones in his figures is 25°—45° to the direction of principal compression. Dunite is not representative of middle or lower crustal rocks and probably deforms more easily, but these experiments indicate that ductile faulting may occur at these depths and much deeper. If this type of deformation is present in the crust below depths at which it is elastic, then there would probably be no major changes in the orientation of throughgoing faults. The Wind River thrust has a fairly uniform dip of 30°—35° deep into the crust as far as we can see on the COCORP seismic reflection profiles. At sufficient depth for high temperatures and pressures, the deformation must be largely in the form of plastic flow. The zone of deformation probably broadens at depth and eventually the stress across it must drop to zero.

Gravity data across the Wind River uplift may be modeled by displacement of dense material along a fault with the same dip as is observed on the Wind River thrust on COCORP seismic reflection profiles (Smithson et al., 1978). The displacement of dense material can occur either in the lower crust or in the region of the Moho but not at both depths. The Moho is estimated to be at 40-km depth from refraction work on the west flank of the Wind River uplift (Braille et al., 1974) and in the southwest Green River basin (Prodehl, 1976). A better fit to the gravity data is obtained if this displacement occurs at lower crustal depths. If near-surface density estimates are correct, this implies that the fault, if it cuts the Moho, does not displace it appreciably at present. There are several possibilities for the behavior of the fault after it disappears from the reflection profiles: (1) it dies out in the lower crust in a broad zone of plastic deformation; (2) it flattens subparallel to the Moho for some distance (the Moho might even act as a movement horizon); (3) it continues to dip at 30°—35° into the upper mantle before dying out. If (3) is the case then any major offset of the Moho must have disappeared, since it is not now observed in the gravity field at the surface. This would suggest that the Moho tends to re-equilibrate itself, if disturbed, and fairly rapidly (here in less than about 60 m.y.) (Smithson et al., 1979).

Prucha et al. (1965) and Stearns (1971, 1975) regarded block faulting of

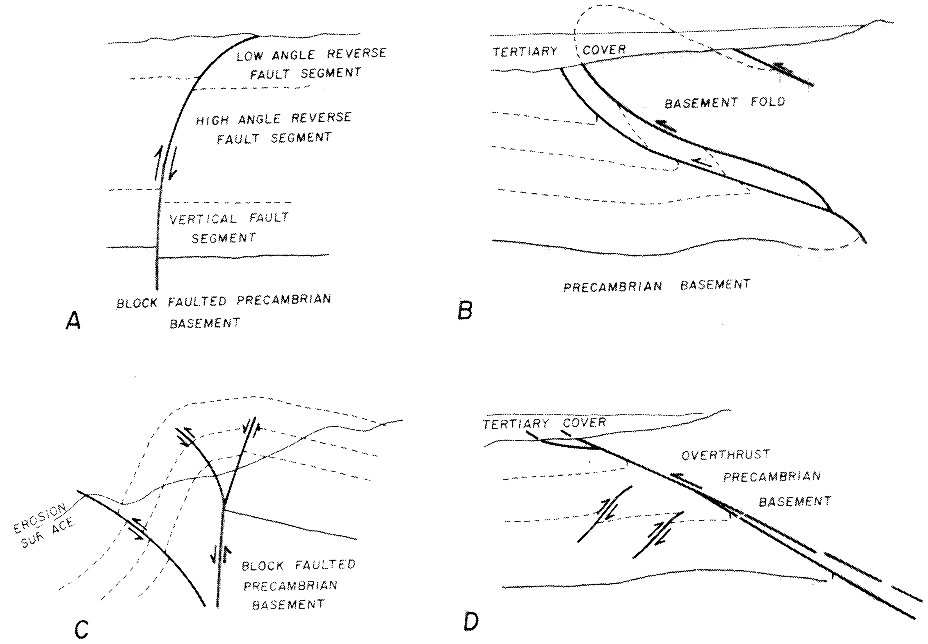

Fig. 9. Proposed styles of Laramide basement thrusts. A. After Prucha et al. (1965). B. After Berg (1962). C. After Stearns (1971). D. Our model for the Wind River thrust.

the rigid basement as the dominant structural style of the Wyoming Province. Thrust faults originate at depths as high-angle reverse faults, then they either flatten to low-angle reverse faults toward the surface (Fig. 9A), or die out in the sedimentary section where deformation is taken up by folding in the Mesozoic and Tertiary sediments (Stearns, 1971, 1975) (Fig. 9C). An important consequence of this type of faulting is that there is little crustal shortening. There is, however, at least 21 km of crustal shortening along the Wind River thrust, and the COCORP profiles show that the fault does not steepen at depth.

Berg (1962, 1963) also considered that Laramide uplifts are possibly the result of vertical tectonic forces, but are "fold-thrusts" occurring along the faulted limbs of huge overturned basement folds. This mechanism is reflected in the sedimentary section by overturned beds under the thrust (Fig. 9B).

On the COCORP profiles the Madison limestone and the top of the basement terminate as horizontal reflecting horizons (Fig. 4, *C* in Fig. 7). Possibly they may be tightly overturned very close to the thrust plane. Surface geology indicates that the Wind River uplift is an anticlinal structure. The COCORP profiles show that thrusting has been the dominant mode of deformation of the Wind River uplift. A certain amount of folding probably occurred before the thrusting, but it was minor compared to the thrust movements.

Any large-scale folding of the basement would probably be reflected in over-printing of tectonic fabrics in exposed basement rocks. This is not recognized in the basement exposed in the Wind River Mountains (Bayley et al., 1973) or in the Wyoming area in general (Hoppin and Palmquist, 1965). Possibly many "fold-thrust" uplifts have a greater component of thrust uplift than has previously been recognized.

Couples (1977) suggests that the asymmetric cross-section geometry of the Wind River uplift can best be modeled by a lower boundary load of similar geometry. This is essentially a modified basement block faulting mechanism and predicts similar fault geometries (i.e., near-vertical at depth).

We see no evidence for Eardley's (1963) suggestion that a large intrusion under the Wind River Mountains was the cause of the uplift.

The Wind River thrust can be traced for a minimum of 55 km along COCORP seismic reflection profiles, and at the base of the sedimentary section at least 21 km of crustal shortening takes place. This represents a minimum upper limit of 35% crustal shortening on this one thrust. The COCORP seismic reflection profiles run approximately from the center of the Green River basin to the center of the Wind River basin. Over the total line length the Wind River thrust represents at least 12% crustal shortening. This is a minimum lower limit. Stearns (1971) calculated 40% shortening in the Rattlesnake Mountains; however, when considering the entire Wyoming region (basins and uplifts) he concluded that 5% shortening was a maximum. The width of the region of Laramide basement uplifts varies from 150—330 km (Burchfiel and Davis, 1975) so that a 5% shortening represents from 8 to 16 km, far less than actually occurs on the Wind River thrust itself. A 12% crustal shortening represents 18—40 km, and a 35% crustal shortening represents 53—116 km. Bally et al. (1966) calculated a maximum magnitude of Laramide shortening in the Paleozoic sediments of about 100 km in Canada. Minimum crustal shortening along the Wind River thrust is at least 20% of this figure and total crustal shortening across the region of basement uplifts may be as large as 100 km.

The Wind River uplift thus reflects fracturing along a major thrust plane of a predominantly rigid Precambrian basement under a strong horizontally directed, compressional tectonic regime. It represents at least 35% crustal shortening under the Wind River Mountains, and we suggest that it may be a model for many of the other large basement uplifts of the Laramide orogeny.

CAUSES OF THE LARAMIDE DEFORMATION IN WYOMING

A major question about the basement uplifts is, how was it possible to produce such a strongly deformed area, with such profound structures as the Wind River thrust producing so much crustal shortening, so far into the middle of the North American craton?

There are three main structural trends in the Wyoming Province, in order of abundance (Blackstone, 1963; Prucha et al., 1965): (1) large northwest-trending crustal structures (e.g., the Wind River Mountains); (2) north—south-trending crustal structures (e.g., Laramide Mountains), and (3) east—west-trending crustal structures (e.g., Uinta Mountains).

Sales (1968) neatly synthesizes these trends into a model in which variable resistance along the North American margin to (uniform) compression from the underthrusting Farallon plate caused a left-lateral shear-couple to be set up between the Canadian shield and the Colorado Plateau. He used scale clay models to indicate that the major features of the Wyoming Province might be produced by this mechanism. The thrusts produced in Sales's models are similar to Berg's (1962, 1963) "fold-thrusts", with the basement behaving in a more mobile fashion than is evident in the Wind River uplift. Possibly Sales's models were not scaled properly.

Stone (1969) explains the diversity of tectonic trends in terms of a north-northeast—south-southwest directed principal horizontal stress. This stress system induces two conjugate sets of strike-slip faults, which result in secondary thrusts and folds (Wilcox et al. 1973). Uplifts thus produced are bounded by high-angle reverse faults (Stone, 1969), but it seems intuitively unlikely that such a profound dislocation leading deep into the crust as the Wind River thrust is an effect secondary to strike-slip faulting. There is also little evidence for large-scale strike-slip faulting in Wyoming.

Evidence exists that during the time of the Laramide orogeny, from about 70 m.y. B.P. to 45 m.y. B.P., the oceanic slab (the Farallon plate) underthrusting the North American continent acquired a shallow dip of about 20° (Lipman et al., 1972; Coney, 1972; Lowell, 1974; Burchfiel and Davis, 1975; Dickinson and Snyder, 1978; Cross and Pilger, 1978). During this time the major calc-alkaline volcano-plutonic fields in the Cordillera migrated to the east with a pronounced magmatic lull in the west. At the time of the Laramide orogeny, magmatic activity occurred in Colorado, ending at about 55 m.y. B.P., and there was also a broad belt of arc magmatism from southern British Columbia to western Wyoming, most pronounced 55—45 m.y. B.P. (Cross and Pilger, 1978). However, in central and southern Wyoming, in the region of basement uplifts, there is no evidence of Laramide magmatic activity.

The cessation of Laramide deformation at about 40 m.y. B.P. coincided with a return westward movement of the calc-alkaline volcanic-plutonic fields of the Cordillera (Burchfiel and Davis, 1975; Dickinson and Snyder, 1978; Cross and Pilger, 1978) as the dip of the subducted oceanic plate steepened again.

This correlation suggests that Laramide deformation was closely connected with the shallowing of the angle of descent of the oceanic plate. There is, however, still the problem of why the basement uplifts were relatively localized and not distributed between the Wyoming region and the site of underthrusting at the western edge of the North American plate.

A possible present-day analogy to the tectonic situation in western North America until the end of the Eocene is the convergence of the Nazca and South American plates (Barazangi and Isacks, 1978). The Nazca plate has about a 10° dip beneath central and northern Peru and central Chile. There is a good corelation between these flat segments of the Nazca plate and: (a) the absence of Quaternary volcanism in the overriding plate above these regions, and (b) considerable seismic activity in the upper 50 km of the overriding South American plate, mostly within the sub-Andean region (Barazangi and Isacks, 1976). In Peru and Ecuador, the sub-Andean fault system is an extensive system of west-dipping reverse and high-angle thrust faults subparalleling the tectonic grain of the Andes (Ham and Herrera, 1963), on average 700 km from the western margin of the South American plate (Burchfiel and Davis, 1976). Earthquake focal mechanisms indicate that the region is in a state of east—west horizontal compression (Stauder, 1975). Megard and Philip (1976) find for northern and central Peru that recent compressional tectonism and lack of calc-alkaline volcanism have a clear relationship to the shallow dip of the Nazca plate. Deformation in the sub-Andean fault system is most intense along its west margin with uplift of Precambrian crystalline rocks and stratigraphic separations of as much as 4.5 km. Not many low-angle thrusts have been recognized, however (Ham and Herrera, 1963).

The basement uplifts of the Laramide orogeny bear a tectonic resemblance to the sub-Andean fault system. Both are products of compressional stresses in the interior of continental lithospheric plates. These stresses appear to be produced at the site of subduction of oceanic plates and enhanced by the very shallow dip under the continent of those oceanic plates.

We suggest the following possible model for the formation of Laramide basement uplifts in Wyoming. As discussed above, the geometry of the Wind River thrust is best explained in terms of horizontal compression. The most obvious origin for this compression is the site of Farallon plate subduction beneath the North American continent. From about 70 m.y. B.P. the Farallon plate under central North America had a shallow dip (about 20° according to Lipman et al., 1972; Dickinson and Snyder, 1978). From 80—40 m.y. B.P. the rate and direction of movement of the North American plate was controlled by the opening of the North Atlantic and Arctic oceans (Coney, 1972). High rates of absolute North American plate motion and high relative rates of underthrusting may have caused the shallowly dipping subduction zone (Cross and Pilger, 1978).

Drag along the bottom of the overriding plate possibly occurred if the Farallon plate had a sufficiently shallow dip (Fig. 10). This drag opposed the North American plate motion, causing a secondary zone of compressive stress to be set up in the North American plate east of the region in which the shallowly dipping Farallon plate started to descend more steeply into the asthenosphere. Magma may have been produced at the point where this occurred. In Wyoming the region of secondary compression was sufficient to prevent this magma from reaching the surface. In Colorado and northwestern Wyoming compression was insufficient, and magmatic activity occurred when the basement uplifts were forming in central Wyoming. Thermal weakening of the lower crust, with zones of decoupling by plastic deformation forming under the compressive stress, may have occurred where magma was prevented from reaching the surface. (A similar mechanism has been proposed by Armstrong and Dick, 1974, to explain thin overthrust sheets of crystalline rocks.) These zones propagated upwards into the more rigid upper crust where they were expressed as major thrust faults such as the Wind River thrust (Fig. 10).

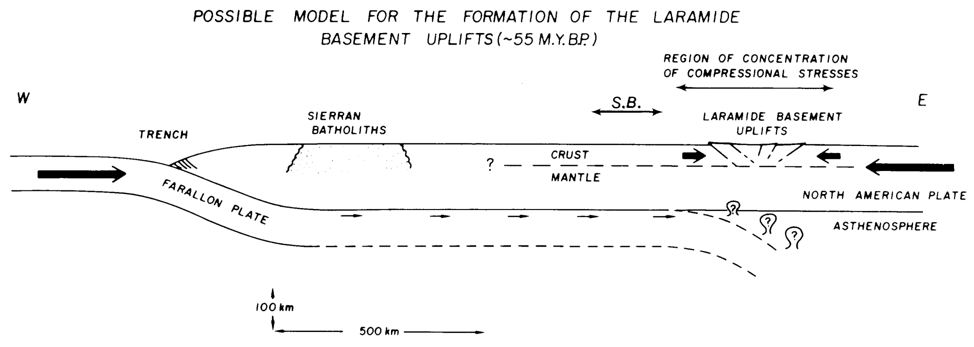

Fig. 10. Possible model for the formation of Laramide basement uplifts (about 55 m.y. B.P.). *S.B.* = position of the Sevier orogenic belt.

This mechanism could also explain why some faults were directed to the east. Hydrodynamic forces might exist between the base of the North American lithosphere and the top of the underthrust oceanic lithosphere (Jischke, 1975; Cross and Pilger, 1978). The easternmost part of the shallow portion of the subducted Farallon plate might therefore have caused a downflexure of the overlying North American plate as it descended into the upper mantle, and possibly this downflexure was sufficient to cause continental crust to the east to override the downflexed continental crust to the west. Possibly the basement uplifts of the Wyoming region represent a primitive intra-continent subduction zone.

This model explains the presence of large basement uplifts far away from the site of oceanic plate subduction — they were caused by a secondary horizontal compressive stress system set up because of drag along the bottom of the continental lithosphere due to the shallow dip of the underthrusting oceanic lithosphere. This compressive system was complementary to the primary compressive stress generated at the margins between the North American plate and the underthrust Farallon plate. The compressive stress system was set up above the point at which the oceanic plate descended more steeply into the mantle, and this explains why the Laramide basement uplifts were so localized.

This model extends previous suggestions (e.g., Dickinson and Snyder, 1978) that basement uplifts were produced by a subhorizontally subducted oceanic plate scraping along the bottom of the overriding continental plate. The importance of buoyant effects of the downgoing slab in producing the diverse tectonic trends of the Laramide orogeny (as suggested by Lowell, 1974) is hard to assess. Stone's (1969) work suggests that the major component of horizontally directed compressions was in a northeasterly direction, which probably represents the relative direction of motion of the underthrust Farallon slab at this time. Coney (1972) documents evidence that between 80 and 40 m.y. B.P. the relative direction of motion of the North American plate was westerly to southwesterly, supporting this suggestion. Although the dominant force causing deformation was in this direction, there must have been many local inhomogeneities in the stress field to have caused the diversity of tectonic trends in Wyoming. Possibly Sales's (1968) left-lateral shear couple between the Canadian shield and the Colorado Plateau may be a mechanism for this diversity. In this case the basement uplifts reflect differential compression of the North American plate as well as being primarily caused by the attitude of the Farallon plate.

CONCLUSIONS

The COCORP deep crustal seismic reflection profiles across the Wind River Mountains have been highly successful in tracing the position of the Wind River thrust. The thrust is a very profound fracture of the continental crust extending to at least 24-km depth along which at least 21 km of crustal shortening has occurred during the Laramide orogeny. The thrust has a fairly uniform apparent dip of 30°—35°. If it cuts the Moho the offset at present is too small to be resolvable from surface gravity measurements. In contrast to most faults in shallow reflection profiles in sediments, the Wind River thrust can be traced as a definite reflection event.

The amount of compression required to produce such a structure must be extremely large. Strong regional compression must have been the dominant tectonic force during the Laramide orogeny in Wyoming. A possible model is a shallowly dipping oceanic plate that drags along the base of the overriding continental plate. A large compressional stress field is set up above the region in which the oceanic plate descended more deeply into the mantle. This caused localized basement uplifts far into the North American plate. Any magma generated by this descending oceanic plate may be prevented from reaching the surface by the compressional stress field.

The resolution of the Wind River thrust deep into the lower crust has very important implications for the amount of deformation that the continental crust can sustain. The COCORP seismic reflection profiles have provided the first close look into the structure and extent at depth of a large thrust fault. They have shown that under large amounts of compression the crust tends to behave in a rigid manner, fracturing along discrete planes. They also show that large thrusts can be formed by compressional forces and that the "mechanical paradox of overthrust faulting" first pointed out by Reade (1908) need not be paradoxical. Because of the moderate dip of the thrust to great depths, the thick upthrust wedge of continental crust had sufficient inherent strength to fracture without buckling. Deep crustal seismic reflection profiling over other major faults might well reveal their extent to similar large depths indicating that the continental crust is deformed by far more continuous structures than has previously been thought possible.

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