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COMPLEX ARCHEAN LOWER CRUSTAL STRUCTURE REVEALED BY COCORP CRUSTAL REFLECTION PROFILING IN THE WIND RIVER RANGE, WYOMING

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A COCORP deep crustal reflection profile across the Wind River uplift crosses exposed Archean rocks and resolves an unusual complex deep crustal structure at a depth of 24–31 km in an area where depth relations in Precambrian rocks can be inferred. The different levels of exposure across the beveled plunge of the Wind River uplift reveal supracrustal rocks at shallower levels with migmatites and pyroxene granulites at deeper levels. For the first time, deep crustal structure from reflection profiling may be interpreted in terms of exposed basement geology. A folded, multilayered deep structure shown by relfection data resembles multiply folded pyroxene granulite interlayered with granitic gneiss exposed in the central Wind River uplift; isoclinal folding is suggested in the folded layered seismic structure. Earlier seismic reflection studies suggested a simpler lower crust. These data indicate that lower crustal structure may have a complexity similar to deeply eroded Precambrian granulite-facies rocks. If this seismic feature represents folded metamorphic rocks, it seems unlikely that this Archean crust could have been thickened by underplating after 2.7 b.y. B.P. and the crust would have to be at least 30 km thich when this structure was formed.

1. Introduction

A major question exists regarding the nature of the lower crust; i.e., whether it shows a complexity similar to exposed granulite facies terrains or whether it is a relatively simple, horizontally layered continuous mafic zone, or possibly a series of alternating layers. This question partly rests on the difference among geologic surface observations, particularly of granulite terrains, limited geologic data from the lower crust such as xenoliths in diatremes and maars [1,2] and observations from the Ivrea zone [3,4], and the fact that interpretation of lower crustal structure must necessarily come from relatively low-resolution geophysical techniques. This study presents results of new and exciting COCORP crustal reflection profiling which has much higher resolution than other geophysical techniques.

Many earlier crustal reflection studies in different countries [5–8] have suggested that a number of reflectors or layers were present in the lower crust. These reflections have commonly been short, near-horizontal segments lacking lateral continuity [7], so that Clowes and Kanasewich [5] suggested that the lower crust contains numerous sills, and Dohr and Meissner [8] proposed that intrusions, magma layers, and slabs of mantle material explain the composite nature of deep crustal reflections. This study, which represented the longest continuous crustal reflection profile recorded, shows strikingly different lower crustal structure. The interpretation is greatly enhanced by the fact that reflections were obtained where Archean crust is spectacularly exposed in the Wind River Mountains in an unusual manner such that relatively reliable three-dimensional inferences may be made about some of the older Precambrian rocks exposed in the United States. Results must, therefore, have important implications about crustal structure in time and space and represent one of the few attempts [9] to interpret crustal structure in terms of exposed basement geology together with seismic reflection data.

2. Geology

The Wind River Mountains are a large Laramide anticline 220 km long and 70 km wide overturned and overthrust to the southwest [10]. Paleozoic through lower Cenozoic sedimentary rocks are involved in the deformation, and erosion has breached the core of the anticline to expose a vast area of Precambrian crust (Fig. 1). The anticline is doubly plunging to the northwest and southeast, and the sedimentary cover can be used to construct the geometry of the fold. This, in turn, allows estimates of relative depth of exposure within the Precambrian rocks.

The size of the Wind River uplift and its sedimentary cover together with geophysical information permits a relatively reliable reconstruction of major fold geometry to be made. Sedimentary rocks wrap around the ends of the uplift (Fig. 1) to show that it is, indeed, a fold structure and allow determination of fold plunge which is about 10° at the southeast end. Most Laramide uplifts in Wyoming started as folds which broke out into a fault on the over-steepened flank as deformation progressed. The seismic reflection data indicate that faulting has greatly predominated over folding in the deformation [11] of the basement. This means that depth of exposure in the Precambrian increases in general from northeast to southwest across the beveled top of the uplift and to the northwest up the plunge of the structure to the approximate middle of the range.

The Precambrian geology holds primary interest for interpretation of the seismic relfections for crustal structure and genesis. The rocks consist of Archean gneisses, some of which are undoubtedly supracrustal, and intrusive granites; a granitic batholith and a pegmatite have been dated at 2.7 b.y. B.P. [12,13]. This area forms some of the older Archean core of the North American craton and is certainly the best exposed Archean crust in the United States. As such it represents a most important area to study crustal structure and growth.

Precambrian rocks at the surface at the southern end of the uplift form a greenstone belt consisting of a relatively simple succession of supracrustal rocks containing amphibolites, greenstone, meta-quartzites, meta-graywackes, iron formation and metadiabase [14]. The rocks are isoclinally folded and dip from 60° to 90° [14] to the northwest. A fault zone cuts these rocks almost parallel to the COCORP profile (Fig. 1) and this area has been interpreted as an Archean suture zone [15]. If this is a suture zone, then depth relationships cannot be readily interpreted across it, but similarity of rock types from the southeast end to the center of the Wind River Range does not indicate that this is a suture.

These rocks are bounded on the north by the Louis Lake batholith, a granitic intrusion dated at 2.7 b.y. B.P. [13]. North of this batholith the geology becomes much more obscure. Most of the range consists of a monotonous series of quartzo-feldspathic gneisses and magmatites in which individual units are difficult to recognize over large areas. These rocks surround another granitic batholith that includes migmatites and trondhjemitic rocks [16]. Yet, fragments of former sedimentary rocks such as pelitic gneisses [17], calc-silicate gneisses [17], and iron formation [18] together with ultramafic gneisses [16] are found scattered in the quartzo-feldspathic gneisses. Migmatites constitute much of the west flank [19] and crest [20] of the range, and the iron formation [18] is swimming in migmatites near the northwestern end of the range. The presence of scattered resistant metasedimentary remnants in magmatites suggests that at least part of the magmatites are formed from sedimentary rocks. A borehole on the west flank of the

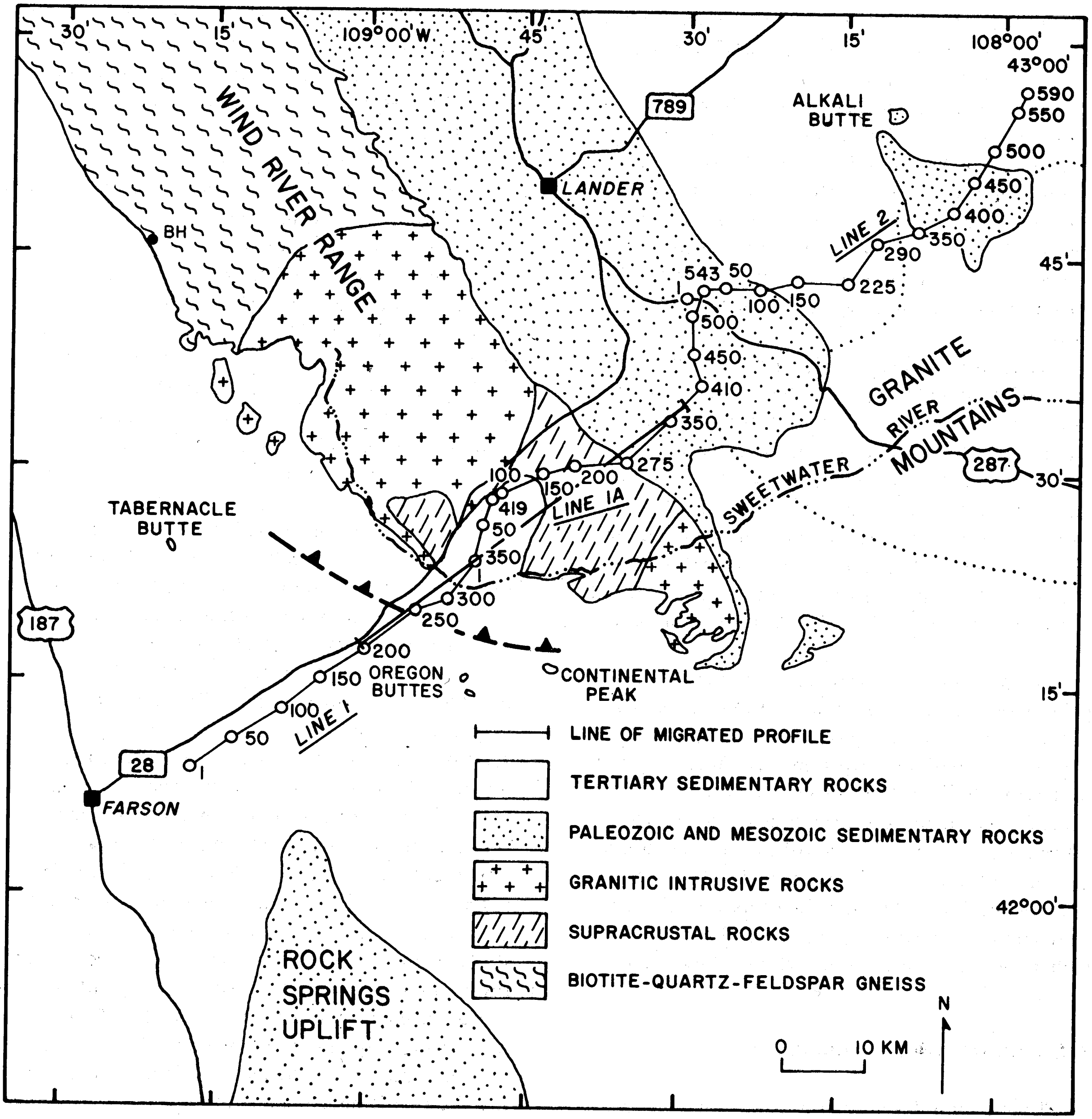

Fig. 1. Location map of COCORP seismic reflection profiles 1, 1A, and 2 traversing the southeast end of the Wind River uplift. Numbers along the lines represent station numbers. Barbed line indicates the trace of the Wind River thrust in the region crossed by the profile. BH is borehole. Shear zone in Precambrian runs close to highway 28 between Lander and Farson.

uplift (Fig. 1) penetrates 3 km of granitic gneisses and migmatites, and similar rocks are exposed in peaks at least 1 km above the borehole [21], so that at least 4 km of these rocks are present in the center of the mountains. Rocks at the bottom of the borehole approach granulite facies mineralogy and pyroxene granulites are exposed in the central part of the range [17]. Metamorphic grade in the southern part of the range near the COCORP line is lower amphibolite to greenschist facies. These geometric and mineralogical relationships show that migmatities and granulite-facies rocks occur at deeper levels in the deeply eroded central part of the range, and lower-grade supracrustal rocks occur down the plunge at the southern end of the range. This agrees with conventional interpretations of metamorphic geology and suggests that rocks found in the center of the range plunge underneath and underlie lower-grade supracrustal rocks at the southern end near the COCORP profile.

Several workers [12,17,19] have found metamorphosed mafic dikes, and Oftedahl [19] suggests two generations of such dikes. A third generation of undeformed dikes is also present. Because of the 2.7-b.y. B.P. age dates are from a granitic intrusive [13] and from Rb-Sr mineral ages on pegmatites [12], these may well only date the final high-temperature event of a long and complex history of deformation, metamorphism, and intrusion. Thus the supracrustal rocks could be distinctly older than the radiometric dates.

The structure of these rocks is complex. Perry [17] recognized early isoclinal recumbent folding followed by open folding on vertical axial planes. A large tabular gabbroic intrusion was affected by both of these folds. Worl [18] also recognized early isoclinal folding in an iron formation and a late open folding around vertical axes. Although steep dips are also present, numerous low dips of 5–30° are found in metamorphic rocks from the deepest levels of exposure (as opposed to predominantly steep dips in higher level rocks at the south end of the range).

3. Seismic reflection interpretation

Readers should note that seismic reflection sections do not show dipping events in their true position or even their true geometry which may be greatly distorted. Migration is the process that correctly done (if the exact velocity distribution is known) places reflections in their true spatial position. Two-way time may be converted to approximate depth by multiplying by 3 km/s. Events may also be recorded whose source lies outside the plane of the seismic section. Without crossline (3-D) control, such side-arriving energy and true dips cannot be resolved; therefore, all dips given here are apparent dips. Limited bandwidth of the input signal and attenuation especially at depth may further limit resolution.

The structures of interest occur on Line 1A, along which Precambrian rocks crop out at South Pass. The entire Wind River profile consists of Lines 1, 1A, and 2, of which Line 1A is treated in this study; the general interpretation of the Wind River thrust and problems found along this profile have been given by Smithson et al. [11,22] and Brewer et al. [23]. The main features seen on Line 1A are the reflection marking the Wind River thrust, which is discussed in more detail in the above references, a number of short shallow reflections, a complex, dipping structure at 7–10 seconds, and deeper short reflections (Figs. 2 and 3).

The upper crust is marked by relatively few reflections (Fig. 2). A few scattered short reflection segments are visible, and one clear long (8 km) reflection dips about 17° between 2.0 and 3.0 seconds (*C* in Fig. 2). Good shallow reflections might be expected based on exposed lithologic contrasts [14] such as quartzite, mica schist, amphibolite and iron formation and based on a local positive gravity anomaly [22] that indicates that mafic near-surface rocks are underlain by more granitic rocks. The gravity anomaly and the interpretation that granitic or migmatic rocks from the center of the uplift pass down plunge underneath the supracrustal rocks near South Pass suggest that reflections might be expected from the base of the supracrustal rocks. Lack of reflections at the presumed base of the supracrustal succession at several kilometers depth is disappointing but not surprising when we consider the isoclinal folding, the near-vertical dips and the possibility that the contact between supracrustal rocks and migmatites or granite may be transitional and complex.

The 8-km-long reflection is strong and almost surprising (*C* in Fig. 2). It is somewhat irregular and consists of a number of cycles as we might expect from layered metamorphic rocks so common in the Precambrian. The number of cycles is caused by layering and the irregularity by some folding and/or the appearance and disappearance of certain layers within a sequence. The event could some from something like iron formation or a mafic dike. The number of

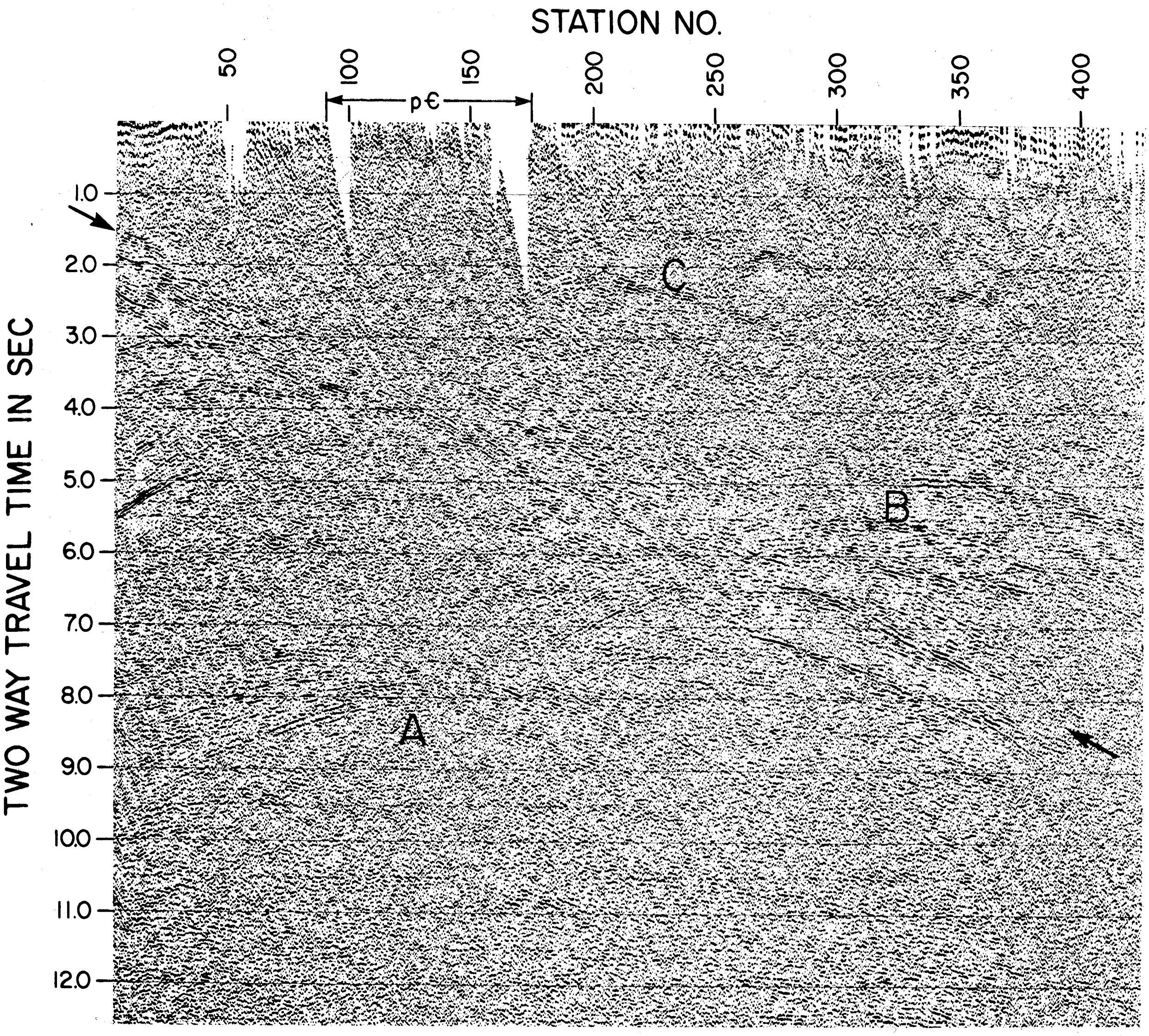

Fig. 2. Unmigrated 24-fold CDP-stacked COCORP reflection profile showing Line 1A. pЄ marks Precambrian outcrop. Arrows Mark reflection from Wind River thrust. Deep complex structure marked by arcuate reflections (*A*) below thrust and by numerous composite reflections (*B*) above thrust. Strong shallow reflection at (*C*).

cycles in the event makes a single mafic dike seem unlikely and would be consistent with iron formation, which could be a strong reflector. Likewise, some other layered metamorphic sequence could generate these reflections. If this reflector is iron formation or other metamorphic rocks then the dip must have decreased sharply from that observed at the surface. This event might also be a fault subsidiary to the main Wind River thrust.

The data between 7 and 10 seconds on Line 1A show a remarkable, complexly layered deep structure (*A* and *B* of Fig. 3). Such features are best interpreted on migrated sections which place reflections in their true spatial position; migration of such data is still in

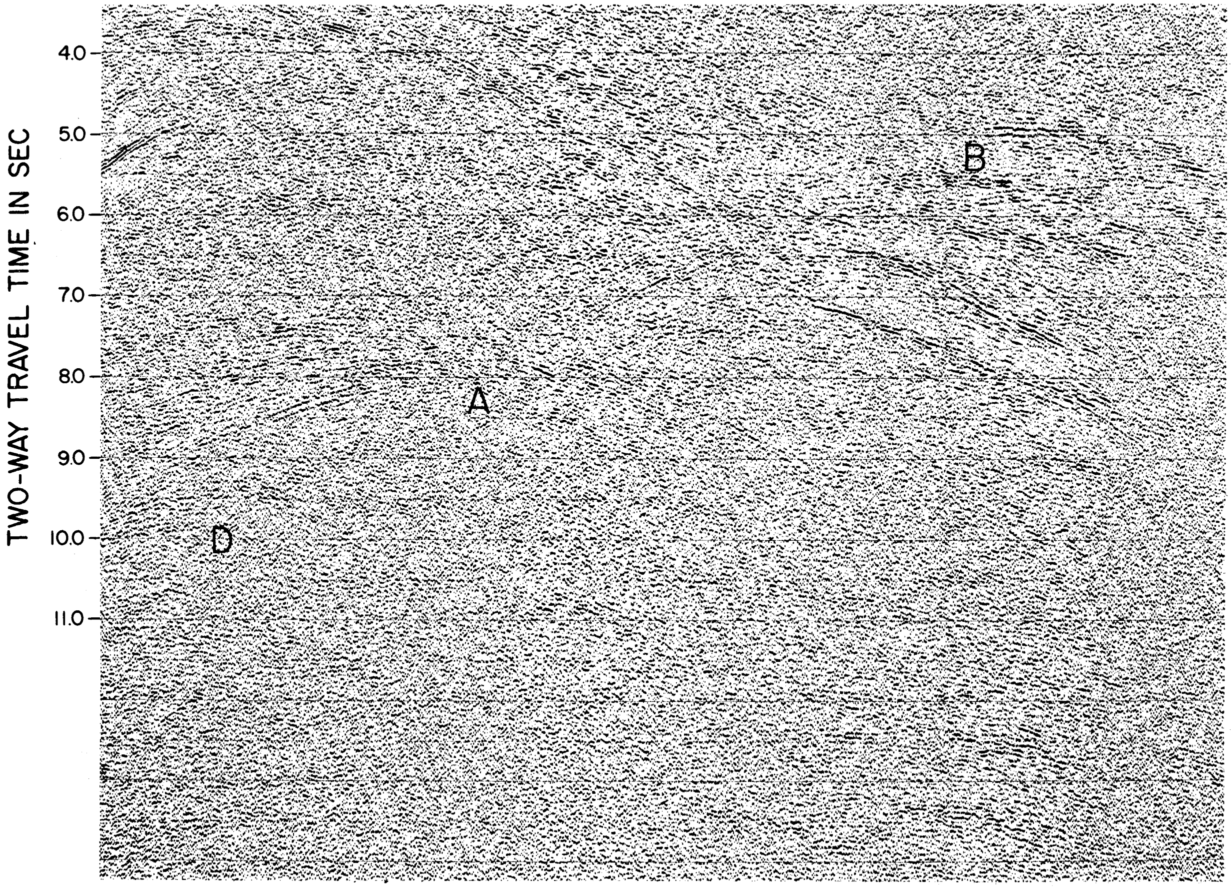

Fig. 3. Close-up of deep part of Line 1A. Arcuate reflection pattern (*A*) and composite reflections (*B*) are same as in Fig. 2. Note short reflection arc at 9.8 seconds (*D*) that intersects broader arc and compare with reflection response (*D*) in Fig. 5. This short reflection appears more clearly on a constant velocity stacked section at 6.7 km/s. Reflection pattern at (*D*) is evidence for isoclinal fold hinge.

the experimental stage. We have therefore performed a simple geometrical migration manually in order to place dipping reflectors closer to their correct position (Fig. 4). These reflections occupy two positions on opposite sides of the thrust (*A* and *B* in Fig. 3), one in the hanging wall between 5.5 and 7.5 seconds (*B*) and the other in the footwall between 7.5 and 10 seconds (*A*). These correspond to depths of about 19–24 km and 24–31 km, respectively. Both features consist of multiple layers indicated by the multi-cycle reflections, and some dips up to 20° and 30° are present.

The deeper structure shows a broad folding that migration moves into a synform. Too much curvature is present for this structure to be a diffraction [24, p. 33]. Reflections converge on the west flank of this structure; the reflection pattern containing convergent dips both on the west flank and across the structure suggests earlier fold hinges (Fig. 5). This structure may plausibly be interpreted in terms of geology exposed up the plunge of the Wind River uplift. The obvious broad-scale folding is a gentle open folding that is late. Convergent dips on the west flank may be vestiges of an early recumbent folding that is generally much more obscure. These are the features that have been reported in deformed gabbros by Perry [17] in the central Wind River uplift. Similar occurrences of gabbro and pyroxene granulite sur-

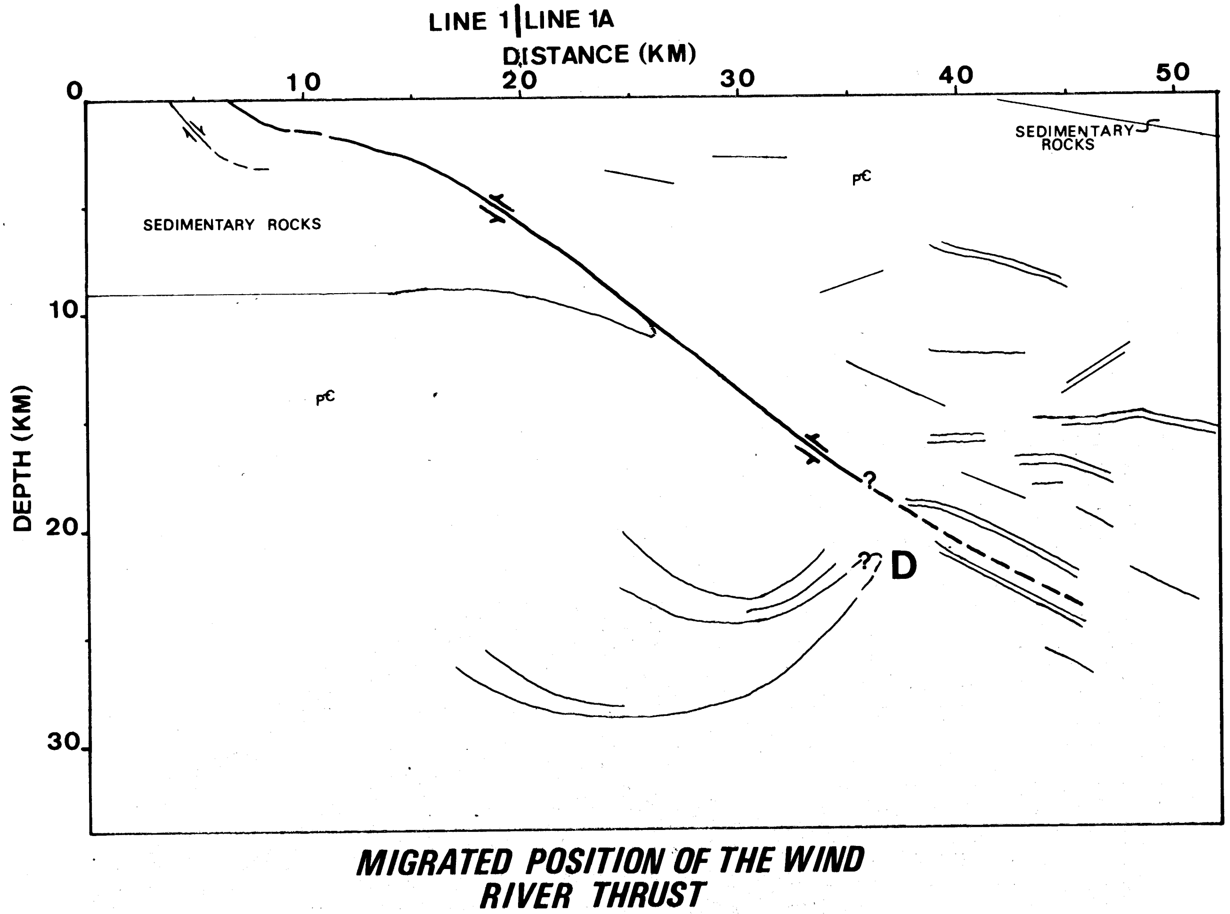

Fig. 4. Migrated position of reflection data projected into a plane that parallels the seismic line marked in Fig. 1. The time section was first converted to depth by using a velocity function varying from 5.8 km/s at the surface to 6.25 km/s at 10 seconds and then the dipping segments were migrated. Maximum apparent dip of the thrust is 38°. Note that convex-upward arcs at 8 seconds migrate into a synform and that an isoclinal fold hinge is inferred at (*D*). The upright open synform corresponds to late deformation recognized in exposed Precambrian of the Wind River uplift.

rounded by granitic gneisses with velocities of about 7.2 and 6.2 km/s, respectively would represent good reflectors in the crust. Reflections could also be generated from iron formation or other metasedimentary rocks as suggested by evidence for multiple layers; presence of metasedimentary rocks this deep in the crust would be an occurrence with important implications for crustal genesis [2,25]. The 8-second group of reflection arcs could even be from one horizon of a synform with a curved fold axis [24].

The best insight into the causes of diffractions and reflections in complex reflection patterns comes from synthetic seismograms (seismic modeling). Fig. 5 presents a synthetic seismogram, generated by wave equation methods with diffraction, of an actual Precambrian multiply-folded recumbent fold from Greenland [27] modeled at a depth of about 14 km. The synthetic seismogram (Fig. 5) illustrates that the reflection pattern from such a structure consists of a series of discontinuous arcs. In general, reflections from synclines are focused and show higher amplitudes than reflections from anticlines [24]. The deep reflection pattern in Figs. 2 and 3 may represent part of a similar structure. And in fact, the convergent arcs

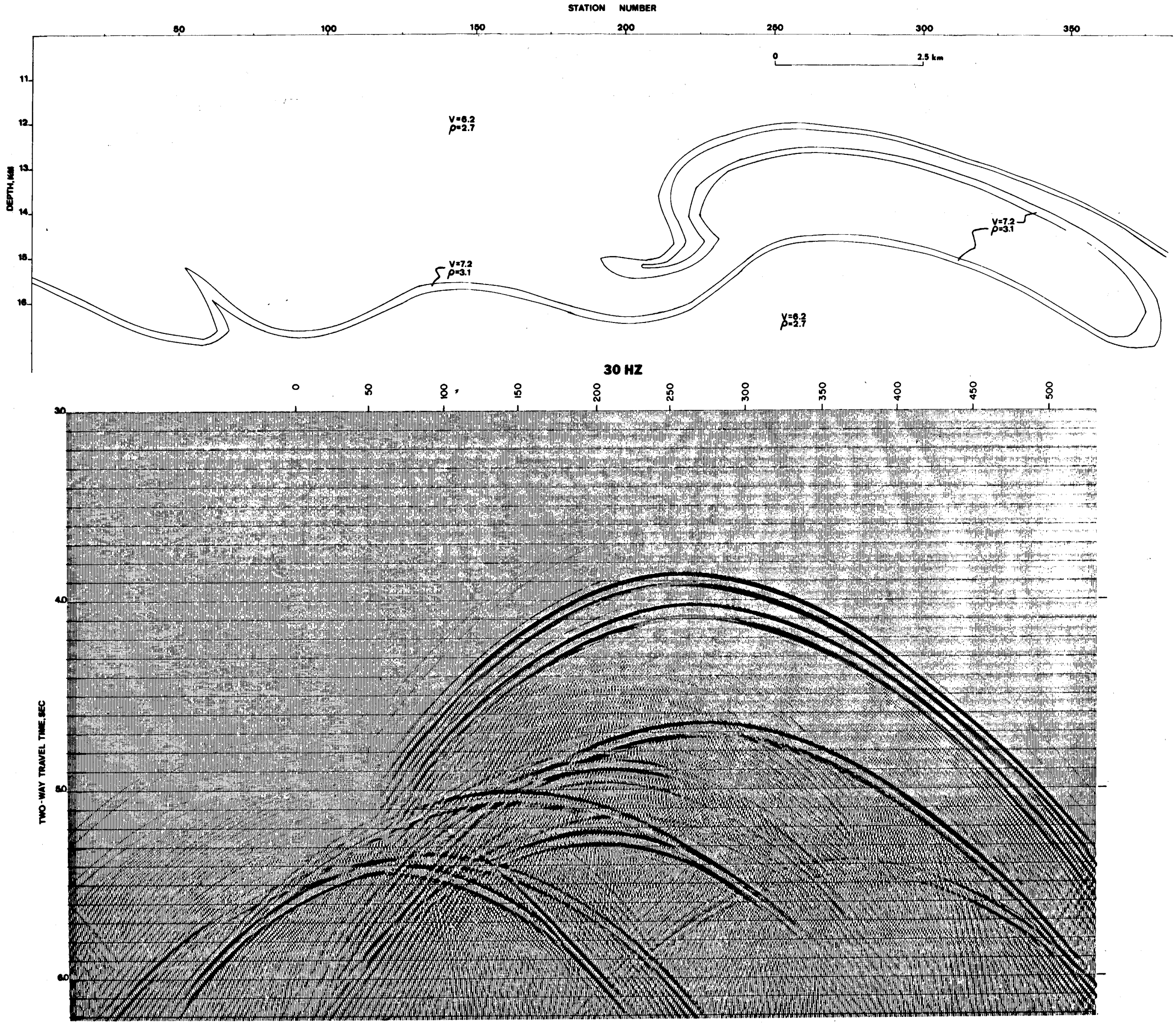

Fig. 5. Synthetic seismogram (seismic model) showing the seismic response of a multiply deformed recumbent fold taken from a mapped structure in the deeply eroded Archean of Greenland. Seismic input pulse has center frequency of 30 Hz. Rock types are pyroxene granulite imbedded in granitic gneiss; true amplitude display. This is not intended to be a direct analog of the deep structure in the Wind River uplift but rather to illustrate the general response of typical folded structures and that reflection pattern is complex. Note that intersection of arcs (*D*) represents an isoclinal fold hinge.

at 10 seconds (Fig. 3) are extremely significant because this pattern is similar to the seismic expression of the isoclinal fold hinge on the right side of Fig. 5. The seismic model does not have the same geometry as the observed reflection patterns and is not intended to be an exact analog for structures in the COCORP Wind River profile, but it does illustrate similarity to the responses for complex metamorphic fold structures found in crystalline rocks.

The other distinctive reflections above the fault (*B*) in Figs. 2 and 3 display a multi-layered character and divergent dips somewhat similar to the other features (*A*). After the reflections are migrated the short steeply dipping (~30°) reflections below the fault (at 6–7 seconds) move across the fault and become part of this same pattern. Our interpretation is to correlate these two reflection patterns (*A* and *B*) across the thrust [26]; if this correlation is correct, it determines a vertical separation of about 6 km across the fault at a depth of 20 km compared with a vertical separation of 9 km at the surface based on offset of the Precambrian.

4. Discussion

The complex structure between 24 and 31 km depth consists of multi-layered rock units which are folded. This can be said with certainty. It is about 20 km below the present eroded Precambrian surface of the footwall. The composition of the layers is less certain but could be pyroxene granulite (metamorphosed gabbroic intrusions) or supracrustal rocks (iron formation, etc.); either of these is plausible based on rock types exposed in the Wind River Range and on reflectivity contrasts. A layered mafic intrusion is another possibility because rocks such as anorthosite, gabbro, and troctolite are found as xenoliths in Pliocene lava flows in the Leucite Hills, 70 km to the south. It is doubtful, however, whether a mafic intrusion would produce a reflection pattern of this strength and geometry. An important point is that the structure is folded and may also be interpreted as being earlier isoclinally folded, a deformational sequence that is also observed in the exposed Precambrian.

For the first time, complex structures in the deep Precambrian crust have been resolved by seismic reflection profiling. These complex structures have been found where the reflection profile went across exposed Precambrian rocks. Previous crustal reflection studies [5–8] have commonly found short (1–2 km) subhorizontal reflectors together with a few short, steeply dipping reflections. These reflection patterns suggested a deep crust different and simpler than that exposed in deeply eroded Precambrian terrains as demonstrated by the seismic model (Fig. 5). *Our results show that crustal reflection profiling is capable of resolving folded structures in the deep crust and that the deep crust has a complexity similar to exposed high-grade Precambrian terrains.*

Attitudes of foliation exposed in the deeply eroded core of the uplift range from sub-horizontal to steep. Although moderately steep dips are present in the reflection data in the deep structure on either side of the thrust, the structure is predominantly horizontal. Steep dips would not be resolved by the present data acquisition techniques so the reader should remember that seismic resolution of dip is biased toward lower dips. Nevertheless, fairly abundant low to moderate dips are present to contrast with the predominant steep dips exposed at the surface along the seismic line. The conclusion is inescapable that steep dips in lower-grade metamorphic rocks at the surface pass into lower dips in higher-grade rocks at depth [25]; these may be the results of horizontal movements in the deep crust.

A suite of crustal xenoliths occurs in the Leucite Hills, a volcanic field located about 70 km to the south. Rock types in the xenoliths include granite and granite gneiss, minor biotite schist, diorite gneiss, pyroxene granulites, gabbro, troctolite, and anorthosite [28–30]. The granite, granite gneisses and biotite schist resemble rocks exposed in the core of the Wind River Range. If we correlate the granitic rocks and biotite schist in the xenoliths with the exposed rocks in the Wind River uplift, which is reasonable, then the other rocks could be representative of deep crust along the COCORP profile. Pyroxene granulites and diorite gneisses, probably together with charnockites, could generate the arcuate deep reflections. These rocks occur together with mafic igneous rocks like gabbro, troctolite, and anorthosite, certain combinations of which might cause observable (but probably weak) reflections at 20–40 km depth.

A major question is the behavior of the lower crust during Laramide deformation. If lowermost crust underwent ductile flow while upper crust behaved brittlely, then deep Precambrian structures would have been overprinted. If crustal thickening by ductile flow during Laramide deformation has taken place, its importance is presently difficult to evaluate.

Our results have important implications for genesis of lower crust in an area that forms some of the older crust in the United States and a possible Archean continental nucleus. The fact that the rocks in the deep crust are folded and that they are layered (Figs. 3 and 4) indicates that this part of the crust has undergone metamorphic recrystallization. Of prime importance is the history of any possible crustal thickening in ancient Archean crust. Fyfe has suggested that early Archean crust was as thin as 20 km because of higher thermal gradients [31] and that crust might be thickened by later basaltic underplating [32]. The concept of thin Archean crust has been questioned by Burke and Kidd [33]. Since the structure resolved in this study is most likely composed of deformed and metamorphosed rocks, it is plausibly associated with the igneous plutonic and metamorphic age dates affecting the surface rocks. Crustal underplating would have to have taken place below the depth of this fold structure. If the early Archean crust were thin, these results provide a minimum age on its thickening. Possibly the earliest Archean crust was thin and a later thickening event corresponds with the deep structure and the 2.7-b.y. B.P. event. Mineral assemblages in schists near South Pass suggest 10–15 km of erosion here. In any case, these results demonstrate that this part of the crust has been more than about 30–35 km thick since at least the late Archean, i.e., about 2.7 b.y.

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