Detailed three-dimensional structure of the deep crust based on COCORP data in the Cordilleran interior, north-central Washington

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ABSTRACT

An unusual opportunity for special processing of selected COCORP data has provided three-dimensional information on deep crustal structure related to Proterozoic rifting, Mesozoic thrusting, and Cenozoic extension in the interior of the United States Cordillera, near the Okanogan Dome, north-central Washington. Using a set of short, intersecting seismic line segments in conjunction with longer regional east-west and north-south seismic lines, we have found dramatic variation vertically in the orientation of structure throughout the crust in this region.

A lower crustal block of south-dipping structures lies above a regionally horizontal Moho found at about 34 km depth. This block is ~13 km thick and is bounded above by a southwest-dipping structure which is discordant to structures both above and below it and is interpreted as a midcrustal thrust formed during Mesozoic to Paleocene convergence. These relationships suggest that the south-dipping lower crustal features were formed prior to, or during, Mesozoic convergence and may be associated either with Proterozoic rifting of the North American continental margin, earlier Proterozoic basement structure, or with a Mesozoic duplex structure formed along a lateral ramp. A zone of relatively few reflections occurs above the mid-crustal thrust and below a highly reflective upper crust and may represent a separate thrust slice in a basement duplex structure. The inferred duplex is cut by east-dipping reflections that project to surface exposures of mylonites and that may be an Eocene(?) normal fault traceable to mid-crustal depths. This duplex structure beneath the Okanogan Dome is analogous to the proposed crustal-scale duplex beneath the Monashee Décollement exposed in a doubly plunging antiform 150 km to the north in the Shuswap Complex. The three-dimensional analysis, along with the southerly plunge of the antiform, indicates that a thrust at depth just south of the United States–Canadian border may be continuous with the Monashee Décollement or with the proposed lower thrusts of the Canadian duplex. If so, then by extending the survey north across the international border, a structure deep in the crust may be traceable to the surface.

INTRODUCTION

This three-dimensional study of the deep crust is an outgrowth of a long, east-west, COCORP deep seismic traverse of most of the northwestern United States Cordillera carried out in 1984 and 1985. Figure 1 shows Phase I of this traverse, consisting of 6 deep seismic reflection lines totaling 296 km in length in northeastern Washington and northern Idaho, the results of which are reported by Potter and others (1986). Based upon published geological information and conventional two-dimensional processing, Potter and others (1986) suggested the presence of a crustal-scale thrust system beneath north-central and northeastern Washington. This thrust system probably extended into the Cretaceous to Paleocene Rocky Mountain thrust belt to the east. East-dipping, deep-crustal reflections beneath easternmost Washington and northern Idaho, probably related to Eocene extension, cut older thrust structures and sole into prominent flat Moho reflections. These observations led Potter and others (1986) to suggest that the Moho formed late in the orogenic history of the Cordillera, probably during Eocene extension. As no cross-lines were included in the initial survey, routine processing of the long east-west traverse provided only two-dimensional information, and much of the interpretation of deep-crustal structure was based on general reflection patterns, with only a few reflections traceable to the surface. For this paper, data for some crooked parts of the line were processed in detail to provide a three-dimensional picture of the crust along part of the transect. The reflections imaged and interpreted in this study provide constraints on various models proposed for deep structure in this region.

The COCORP data used specifically in this study are from north-central Washington north of the Okanogan Dome crystalline complex. They include the eastern end of Washington Line 1, the western end of Washington Line 2, and Washington Line 8 (Fig. 2).

This study is perhaps the first deep seismic study to demonstrate systematic three-dimensional variation in orientation of deep-crustal structures. Together with the numerous surface geological studies of exposed cross sections of the deep crust, these data attest to the structural complexity of the deep crust in areas that have experienced a complex tectonic history.

GEOLOGIC SETTING

The COCORP transect in northeastern Washington and northern Idaho crosses the southern part of the Omineca Crystalline Belt (Fig. 1). This part of the Omineca Belt lies just to the east of the western edge of Precambrian continental crust inferred from initial strontium ratios (Armstrong and others, 1977) and is characterized by the exposures of several high-grade metamorphic complexes. Three of these complexes are crossed by the COCORP lines: the Okanogan Dome, the Kettle Dome, and the Priest River Complex (Fig. 1). Most of the rocks of these complexes are amphibolite-grade metamorphic rocks of probable or proven Precambrian age. The Priest River Complex contains Proterozoic sillimanite- and kyanite-bearing gneisses (Clark, 1973; Rhodes and Hyndman, 1984),

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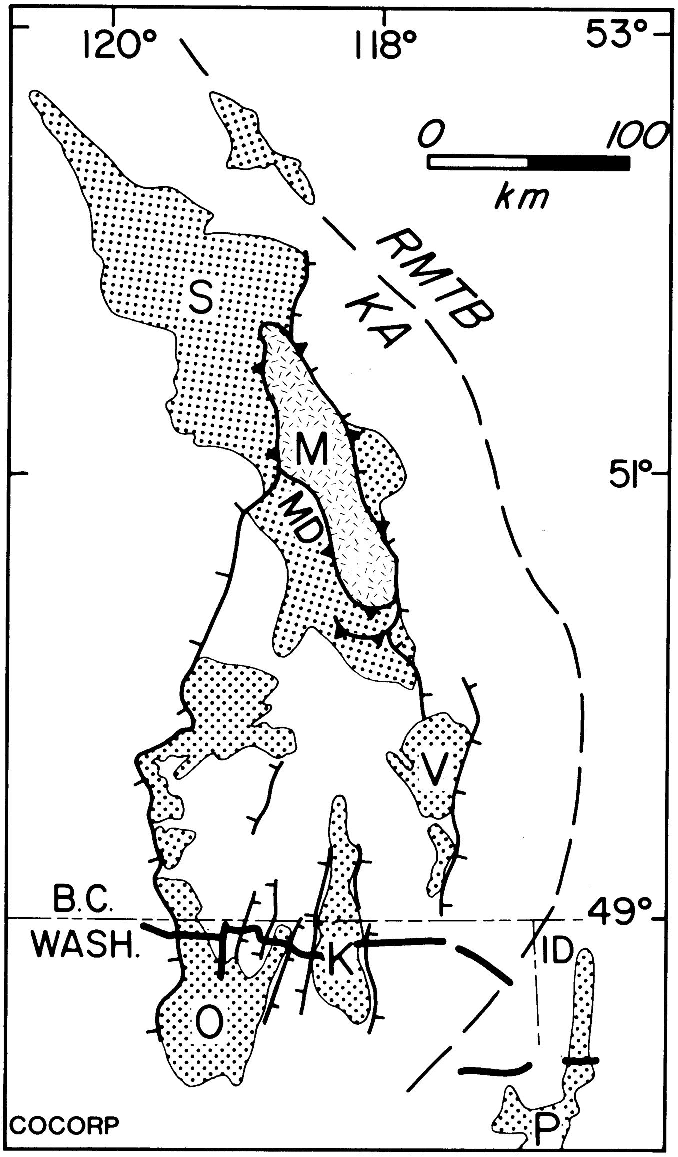

Figure 1. Generalized map of the southern part of the Omineca Crystalline Belt (Shuswap Complex) showing the culminations of high-grade metamorphic rocks, the major structural features, and their relationship to the COCORP lines. Cretaceous to Paleocene compressional structures trend northwest and Eocene extensional structures trend north to northeast. M: Monashee Complex; S: Shuswap Complex; O: Okanogan Dome; K: Kettle Dome; V: Valhalla Dome; P: Priest River Complex; KA: Kootenay Arc; RMTB: Rocky Mountain Thrust Belt; MD: Monashee Décollement. Solid heavy lines denote seismic line locations; lines with barbs denote normal faults, with barbs on down-thrown side; teeth denote thrust faults, with teeth on upper plate; dots: culminations of high-grade metamorphic rocks; random dashes: Archean and Proterozoic gneisses of the Monashee Complex. Map after Journeay and Brown (1986) and Okulitch (1984).

whereas the Okanogan and Kettle Domes contain rocks which are lithologically similar to those of the Priest River Complex (Cheney, 1980; Orr, 1985). The rocks of all three metamorphic complexes exhibit Jurassic through Eocene ages of metamorphism and cooling (Okulitch, 1984; Fox and others, 1977; Cheney, 1980). Surrounding the metamorphic complexes are Paleozoic-Mesozoic low-grade phyllites, limestones, and greenstones considered to be part of an accreted terrane [(Quesnellia; Tipper and others, 1981), part of Terrane I = Intermontane Terrane (Monger and others, 1982; Price and others, 1985)]. Overlying Paleogene volcanic and nonmarine sedimentary rocks were deposited in structural lows formed during Eocene extension and magmatism. The metamorphic complexes have a relatively unmetamorphosed upper plate separated from a lower plate of high-grade metamorphic rocks by Eocene chlorite breccias and commonly have thick mylonitic zones at their margins (Cheney, 1980; Rhodes and Cheney, 1981; Orr, 1985). These characteristics are similar to those of the metamorphic core complexes exposed throughout a large part of the interior of the North American Cordillera (Crittenden and others, 1980; Armstrong, 1982).

The southern part of the Omineca Belt lies within the interior of the Cordillera between the Rocky Mountain thrust belt to the east and the accreted terranes to the west; this part was a site of Jurassic through Paleocene crustal shortening and thickening (Brown, 1981; Price, 1981). Mesozoic convergence of large magnitudes relative to the North American craton has been documented for both the thrust belt and accreted terranes. Some of the related shortening was apparently accommodated in the Cordilleran interior by development of a crustal-scale duplex (Read and Brown, 1981; Monger and others, 1985; Brown and others, 1986; Potter and others, 1986) just eastward of the pre-Mesozoic continental margin beneath the easternmost accreted terrane (Intermontane Terrane of Price and others, 1985), which was thrust across the continental margin (Monger and others, 1985; Brown and others, 1986).

A regional Bouguer gravity high is associated with the southern Omineca Belt, with individual metamorphic complexes marked by local gravity highs (Cady and Fox, 1984). From models based on limited seismic refraction data and gravity data, Cady and Fox (1984) have suggested that the metamorphic complexes are the surface expression of a zone of dense infrastructure comprising the upper 20 km of the crust in this region.

The deepest major thrust exposed in the Shuswap Complex is the Monashee Décollement (Figs. 1 and 3), marked by a mylonitic zone up to 1 km thick exposed in a doubly plunging antiform. The Monashee Décollement was a major mid-crustal thrust which accommodated easterly directed thrusting during the Early Jurassic (Read and Brown, 1981; Brown and Read, 1983; Okulitch, 1984). Movement on the décollement (MD1) apparently ended by Late Jurassic time (Brown and others, 1986). There is evidence of reactivation of the thrust at higher levels in Late Cretaceous time, however (MD2, Journeay and Brown, 1986). In order to account for the greater than 100 km of Late Cretaceous through Paleocene displacement documented for the Rocky Mountain thrust belt to the east, Brown and Read (1983) proposed the existence of a sole thrust beneath the Monashee Décollement to accommodate this displacement. In other models based upon palinspastic reconstructions using surface geologic and seismic refraction data, Brown and others (1986) and Monger and others (1985) proposed that this displacement was taken up on several deeper thrusts, producing a crustal duplex beneath the Monashee Décollement (Fig. 3).

Some of the earlier Jurassic obduction-related structures separating Intermontane Terrane from North America may be exposed in the area of the COCORP lines in northeastern Washington (Orr, 1985; McMillen, 1979; Okulitch, 1984). The COCORP data suggest that thrusts which probably tie into the Cretaceous to Paleocene Rocky Mountain thrust belt also occur at depth beneath this area (Potter and others, 1986).

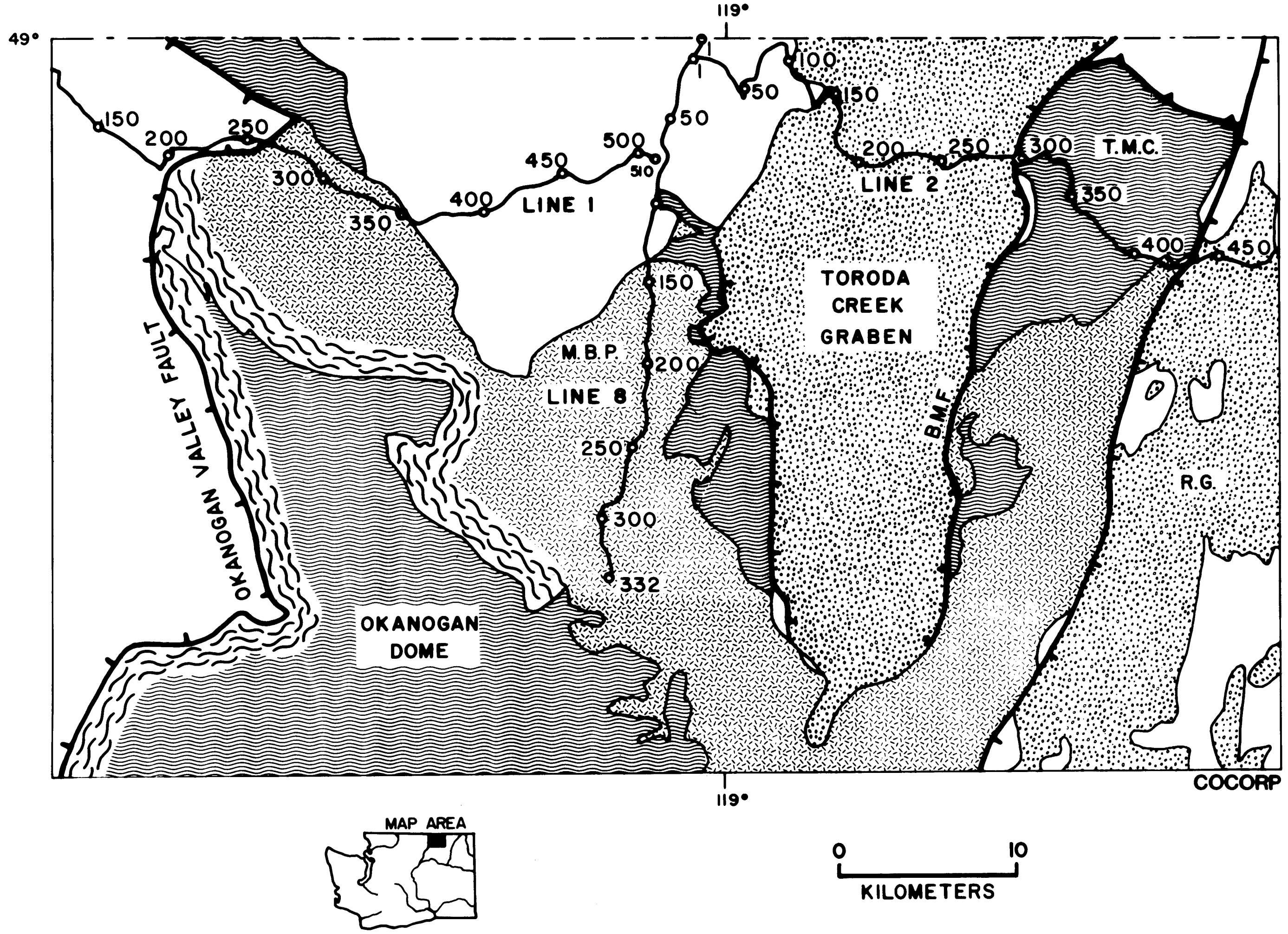

Figure 2. Local geologic map of the northern edge of the Okanogan Dome with the locations of the COCORP lines used in this paper. TMC: Tenas Mary Creek group; RG: Republic Graben; MBP: Mount Bonapart pluton; BMF: Bodie Mountain fault. Lines with open circles and numbers: COCORP lines with station numbers; lines with barbs: normal faults, with barbs on down-thrown side; lines with teeth: thrust faults, with teeth on upper plate; wave pattern: amphibolite-facies gneisses; random dashes: plutonic rocks; pebble pattern: Eocene volcanics and sedimentary basin fill; white: Paleozoic and Mesozoic accreted rocks; sigmoidal pattern: mylonites. Map after Cheney (1980), Orr (1985), Fox and others (1977), Waters and Krauskopf (1941), and Snook (1965).

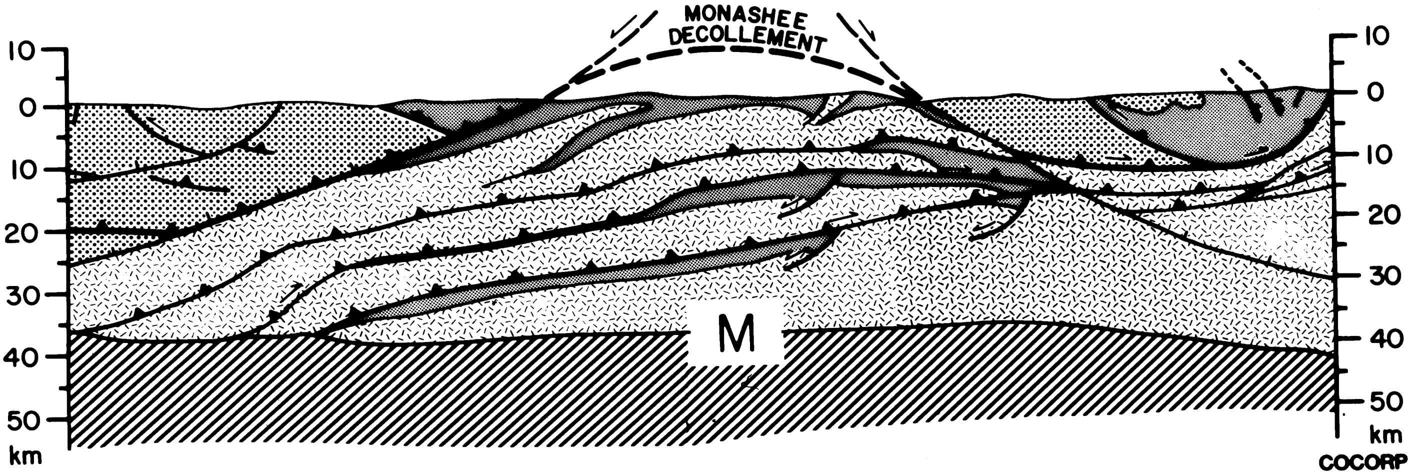

Figure 3. Crustal-scale cross section across the Monashee Décollement and Monashee Complex from Monger and others (1985). Teeth denote thrust faults; barbs denote normal faults; movement on faults in direction of arrows. Dots: accreted Paleozoic and Mesozoic rocks (Terrane I = Intermontane Terrane, Price and others, 1985); dashes: high-grade metamorphic rocks, perhaps related to Proterozoic continental margin of North America; fine stipple: Proterozoic marginal deposits, correlative to Belt Supergroup.

The COCORP lines which comprise this 3-D study cross part of the Okanogan Dome and adjacent upper-plate rocks (Fig. 2). The Okanogan Dome is bounded by two large Eocene extensional features. The Okanogan Valley fault on the west (Fig. 2) is a shallow, west-dipping normal fault (Bardoux, 1985) exposed in the Okanogan River Valley and can be followed northward over 200 km into southern British Columbia to a position just west of the Monashee Complex (Fig. 1) (Journeay and Brown, 1986). This fault may have had as much as 90 km of displacement on it (Tempelman-Kluit and Parkinson, 1986). The Toroda Creek Graben, to the east (Fig. 2), is a large half-graben which is cut by a series of down-to-the-west normal faults mapped to the north in the Greenwood map area of southern British Columbia by Monger (1968). The oldest K-Ar and fission-track ages in the Okanogan Dome are Cretaceous; however, biotite and hornblende K-Ar ages in the gneisses are Eocene (Fox and others, 1977). These ages suggest that a major metamorphic and plutonic pulse occurred during Cretaceous convergence. Uplift then culminated in the Eocene, when the rocks passed rapidly through the Ar blocking temperatures for both hornblende and biotite (Fox and others, 1977).

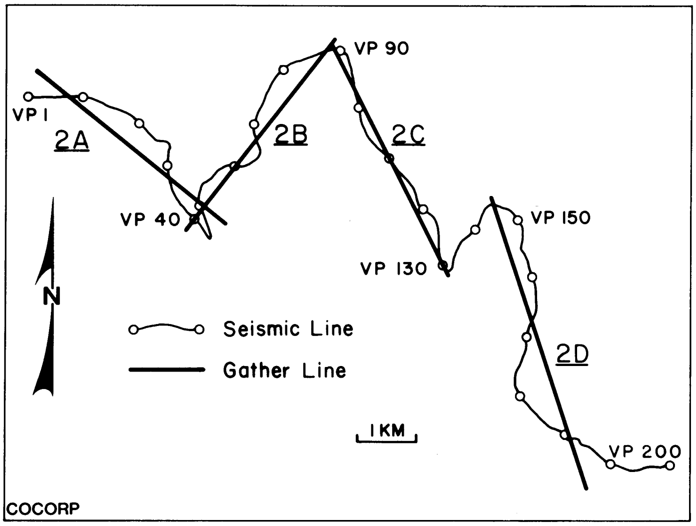

Figure 4A. Map of the crooked line geometry of the western end of Washington Line 2 showing how this segment was divided into four sub-lines (2A, 2B, 2C, and 2D).

TECHNIQUE FOR PROCESSING CROOKED SEISMIC LINE

COCORP seismic surveys typically employ the common mid-point (CMP) method which produces redundant reflection data for a set of subsurface points. The CMP stacking method is normally most appropriate when the seismic surveys are run along straight lines. COCORP commonly designs the first stage of its surveys, which is for the purpose of reconnaissance, to be run along lines which are as straight as possible and as close to perpendicular to the strike of surface structures as logistics allow. Later, cross-lines and additional dip lines are sometimes run to obtain three-dimensional information in selected areas. In the region of this study, straight seismic-line geometries were not possible because of mountainous terrane. The line geometry of the western end of Line 2 is especially crooked, consisting of several fairly straight segments connected by sharp bends (Figs. 2 and 4a).

During conventional processing, the crooked geometry of the western end of Line 2 resulted in an extremely high maximum stacking fold (>200 traces per CMP compared to the nominal full-fold value of 48). Figure 4b is the mid-point scatter diagram for this segment of Line 2. This figure

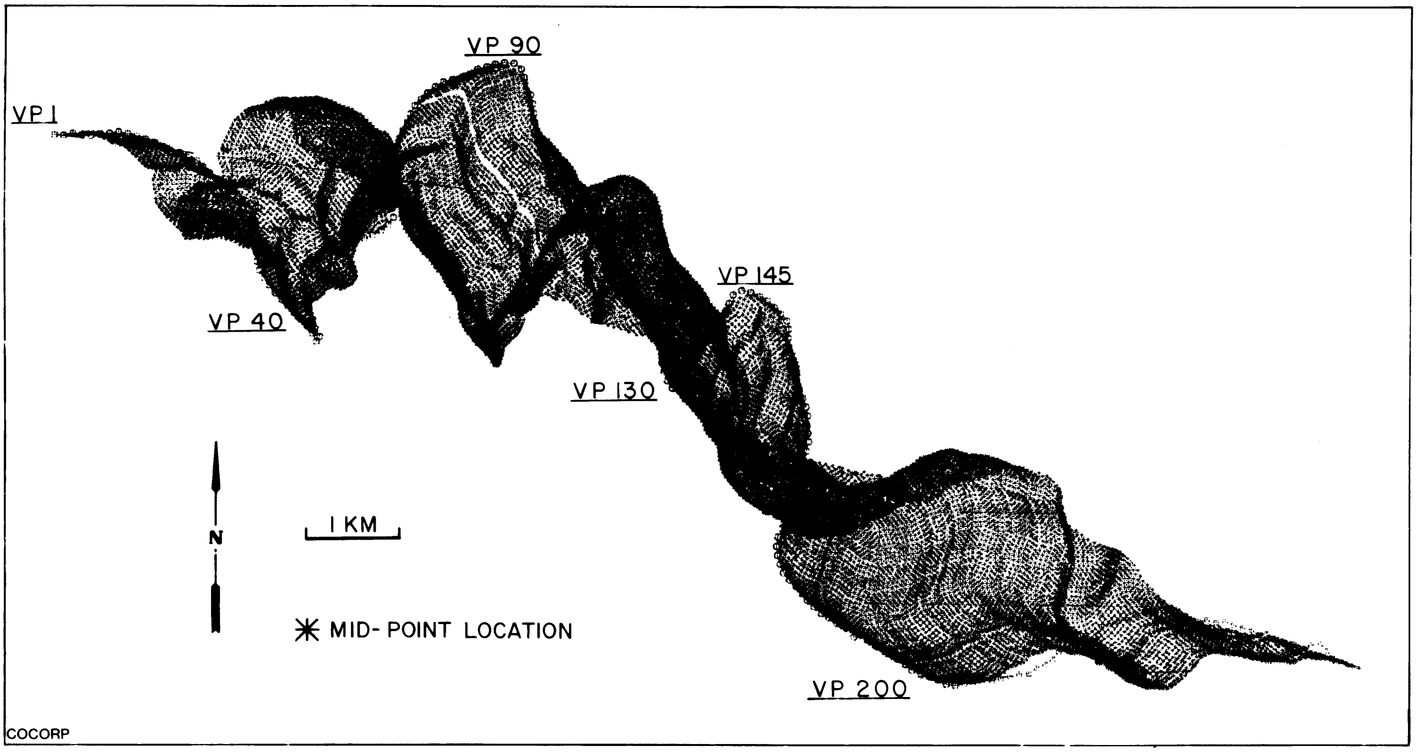

Figure 4B. Mid-point scatter diagram for the full-fold data of the western end of Washington Line 2.

illustrates that a great deal of CMP scatter would occur regardless of the gathering direction. In order to reduce CMP scatter and to provide three-dimensional information on crustal structures for this paper, the westernmost 204 vibration points (VP's) of Line 2 were divided into four sub-lines (2A, 2B, 2C, and 2D) as shown in Figure 4a. In order to minimize CMP scatter in a particular sub-line, only data from shots and receivers within that segment were used. For a given shot-point gather, all traces which corresponded to receivers outside the line segment were zeroed. Each sub-line was then gathered and stacked as a separate line.

The four resulting sub-line stacks provide an opportunity to determine three-dimensional geometries of deep reflectors. These stacks are displayed side-by-side in Figure 5 in order to compare the apparent dips of reflections on adjacent sub-lines. Reflections occur throughout the time sections to greater than 11 s.

Correlations of reflections between sub-lines were made on the basis of one or both of the following criteria:

1. The reflection can be traced across at least three of the sub-lines with no more than 20 ms time difference between sub-lines.

2. If seen on only two sub-lines, then the reflection must also be seen on the full-fold stack of Line 2, or on shot point gathers. These criteria were used in order to ensure that the reflections traced across sub-lines represent the same structural feature.

The attitudes of the reflectors were determined using the intersecting seismic line method (Slotnick, 1959; de Voogd and others, 1986). Three main assumptions are made in application of this method: (1) the reflectors are relatively planar; (2) the seismic waves have traveled their entire path through a medium of constant velocity; and (3) the reflections occurred at normal incidence to the reflector.

The apparent dip of each reflection was calculated for each of the sub-lines on which the reflection was observed. As the orientation and apparent dips on each sub-line are known, the true strike and dip of the reflector can be determined. After the strike and dip are known, the depth to which a reflection point migrates can be determined, as can the surface location vertically above the migrated reflection point. Therefore, a set of 3-D coordinates can be determined for any reflection point. These coordinates specify the position of the reflector subject to the accuracy of the above mentioned assumptions.

As the shot-to-receiver offsets for these short sub-lines are small compared to the depths of the middle and lower crust, the reflections received are fairly insensitive to changes in stacking velocities (for stacking velocities greater than about 5.5 km/s). Therefore, a large uncertainty would be associated with interval velocities calculated from these stacking velocities. Because of these large uncertainties, the velocities used to determine the apparent dips of reflections on each sub-line were those found by Hill (1972) from a long-offset refraction study across this region. That study found the crust to consist of two layers, a 6.0 km/s layer at a depth of 0–22 km above a 6.6 km/s layer at a depth of 22–34 km. The Moho was interpreted to lie at 34 km depth, where the refraction velocity increased to 7.9 km/s. The velocities used to determine apparent dips were 6.0 km/s for reflections with travel times less than 7 s (21 km depth) and 6.6 km/s for reflections with travel times greater than 7 s.

The migrated positions of reflection points were found by using a constant velocity of 6.0 km/s for reflections arriving earlier than 7 s. For reflections arriving later than 7 s, a constant velocity of 6.2 km/s was used to migrate reflection points. This value is the average velocity of the crust in this region as reported by Hill (1972). Wavefront charts constructed for this velocity model demonstrate that, for reflectors with true dips of less than 60°, little error occurs in locating reflection points using the average velocity. In any case, because much of the present interpretation of the reflectors is based upon their strikes, dips, and geometrical relationships to other reflectors, the error is not important to the main conclusions of this study.

In the following, the sub-lines discussed above are used along with the full-fold stacked sections of the eastern end of Washington Line 1 and Washington Line 8 to determine the three-dimensional reflection geometry of the crust beneath the Okanogan Dome metamorphic complex. Interpretations of the data were made using the three-dimensional information along with local and regional geologic data.

DATA DESCRIPTION AND REFLECTOR GEOMETRIES

The unmigrated sub-line, stacked seismic sections displayed in Figure 5 clearly demonstrate the complex reflector geometry beneath the study area. Unmigrated sections of the eastern end of Line 1 and the western end of Line 2 are displayed in Figure 6; Line 8 is displayed in Figure 7. Generalized line drawings of these sections are displayed in perspective view in Figures 8 and 9 to illustrate the relationships of reflections between seismic lines of different orientations. All of these figures show that the crust in this area consists of alternating layers of subhorizontal and dipping reflections. The reflections seen on these sub-lines are believed not to be diffractions because (a) the dipping reflections do not match diffraction curves plotted for the appropriate velocities and travel times and (b) the horizontal reflections can be traced as planar features for considerable distances on the full-fold stacked sections in the areas where the line is extremely crooked. Following is a description of the reflection data and the geometries of reflectors determined by the method previously described, beginning with the uppermost reflections and continuing down through the crust.

Reflections A are seen on sub-lines 2A, 2B, and 2C (Figs. 5 and 8) between 1.2 and 1.8 s two-way travel time. The reflectors producing A are at a depth of 3 to 5 km, strike N50°–55°E, and dip moderately 18°–23° to the northwest. The same reflections are on the full-fold stack of Line 2 beneath VP's 1–120 (Fig. 6) and die out to the east beneath the western edge of the Toroda Creek Graben. Reflections with an apparent northward dip occur on the northern end of Line 8 (reflections A′) and have the same travel times as reflections A on Line 2 at the intersection of Lines 2 and 8 (Figs. 7 and 8). Reflections A′ project to the surface near where Line 8 crosses the mapped edge of the Okanogan Dome (VP 130; Figs. 2 and 7).

Reflections B are subhorizontal to moderately dipping reflections between 1.5 and 4.5 s on the southern half of Line 8, beneath the surface exposure of the Okanogan Dome (Figs. 7, 8, and 9). There is no three-dimensional control on this segment of Line 8; however, the majority of these reflections above 5 s are horizontal or have gentle apparent dips to the north. There are a few south-dipping reflections also present, suggesting an imbricated pattern of reflectors.

A series of reflections is present on the sub-line stacks between 2.5 and 4.0 s two-way travel time (reflections C; Figs. 5 and 8). Reflections occurring between 3 to 3.2 s within zone C are subhorizontal. Beneath these subhorizontal reflections, there are gently southwest-dipping (< 10°) reflections which appear to merge in the updip direction with the overlying reflections. Reflections C as seen on the full-fold stack of Line 2 die out beneath the eastern side of the Toroda Creek Graben at about VP 230 (Fig. 6). Subhorizontal reflections on the northern end of Line 8, where Line 2 intersects Line 8, at 2.5 to 4 s are probably equivalent to reflections C on the sub-lines (Fig. 7). Reflections at 2 to 2.5 s beneath VP 425 on the

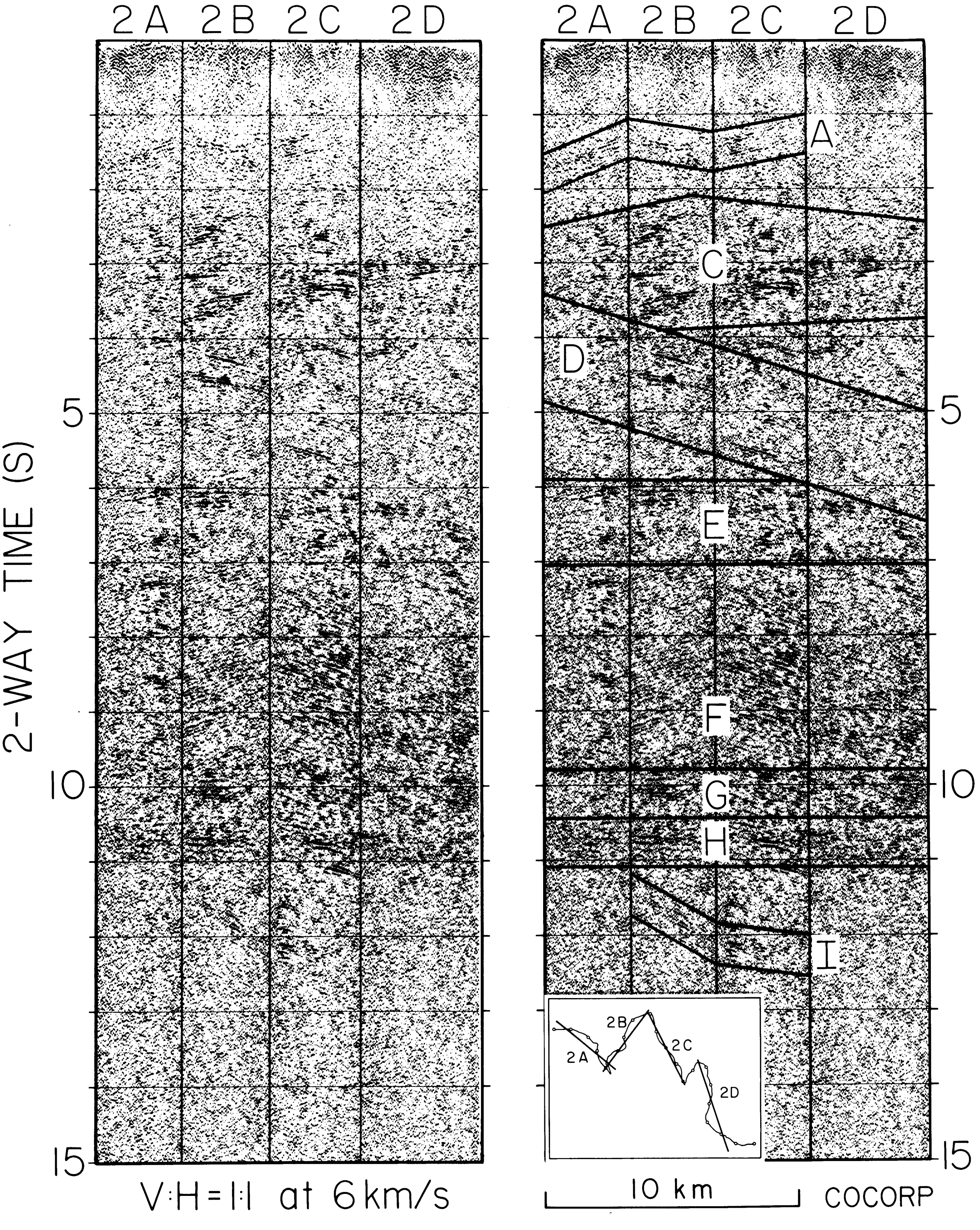

Figure 5. Unmigrated, stacked sections of the four sub-lines from the western end of Washington Line 2. The sections on the right are the same as those on the left but with reflection zones outlined.

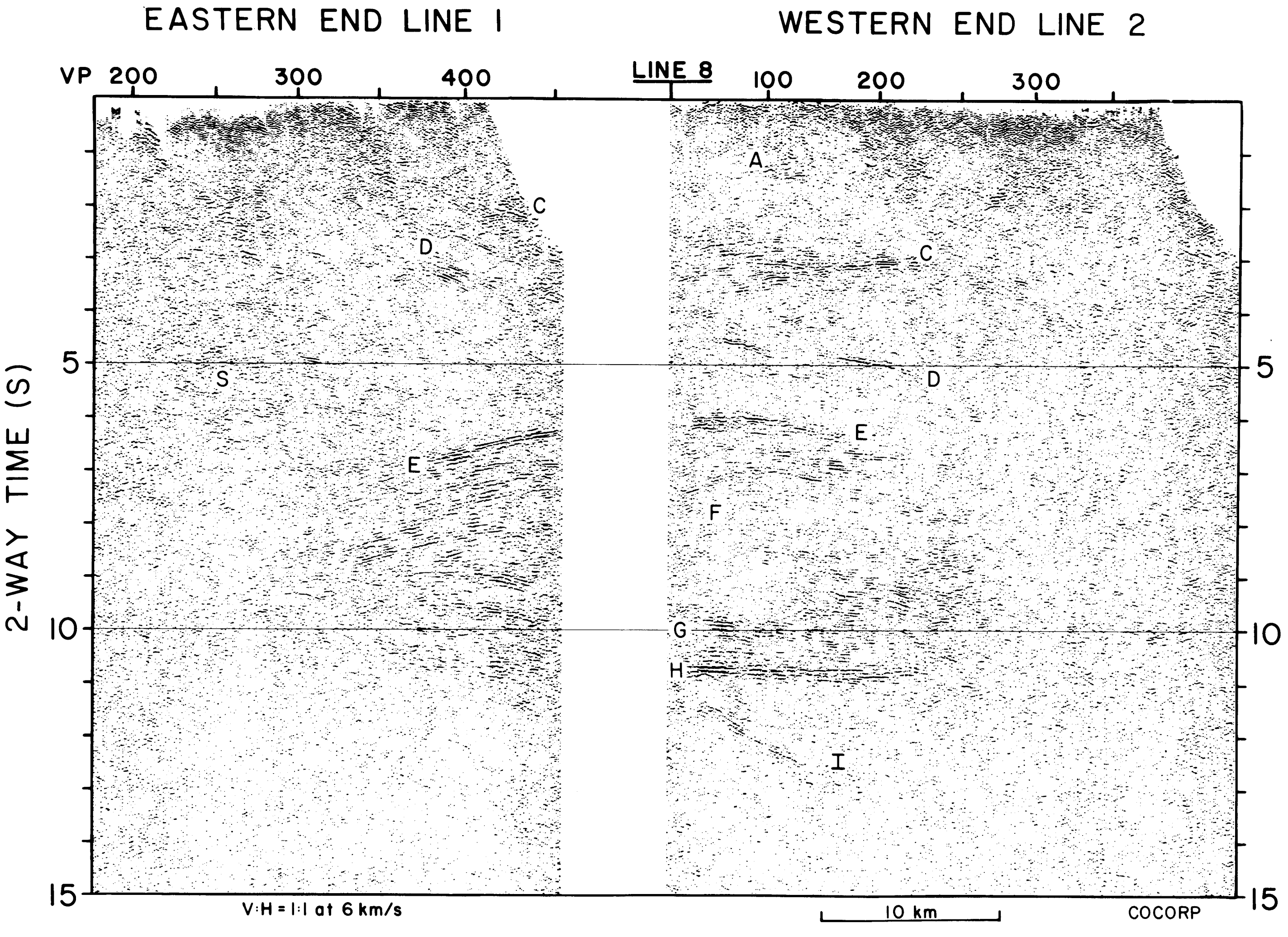

Figure 6. Unmigrated, coherency-filtered, full-fold, stacked sections of the eastern end of Washington Line 1 and the western end of Washington Line 2. Letters refer to reflection zones discussed in the text.

eastern end of Line 1 appear to be the western continuation of reflections C seen on the stack of Line 2 (Fig. 6).

Reflections D occur beneath reflections C between 4.5 and 6 s on the sub-line stacks (Fig. 5). The reflectors producing D on the sub-lines have a north-south strike and dip 30° to 35° to the east. Reflections D are the only prominent reflections seen between 4 and 6 s beneath the western end of the full-fold stack of Line 2 (Fig. 6). Reflections with apparent dips to the east are also seen beneath VP's 350–425 on the eastern end of Line 1 between 2 and 4 s (Fig. 6). These reflections appear to truncate overlying reflections that have been correlated with C on Line 2 (Fig. 6). These east-dipping reflections on Line 1 are correlated with reflections D seen on the sub-lines and on the full-fold stack of Line 2.

Strong, mid-crustal reflections (E) occur on all sub-lines at travel times between 6 and 7 s (18–21 km depth; Fig. 5). The zone of reflectors producing E is subhorizontal and is ~3 km thick. Corresponding reflections occur at the same travel times on Lines 1, 2, and 8 (Figs. 6, 7, 8, and 9). On Lines 1 and 8, reflections E are accompanied by strong diffractions, which collapse upon migration. E has an apparent dip to the west beneath Line 1 (Fig. 6) and to the south beneath Line 8 (Fig. 7), indicating that it was produced by a zone of reflectors which strikes approximately N55°W and dips about 15° southwest, which is approximately parallel to the regional strike of the Rocky Mountain thrust belt.

The most prominent group of reflections seen in this study is labeled F on the sub-lines between 7 and 10 s (Figs. 5 and 8). Similar reflections are seen on the northern end of Line 8 at the same travel times (Figs. 7 and 8). The reflectors producing F have an approximate east-west strike and dip 28°–30° to the south. This east-west strike occurs in a region where the surface features strike approximately north-south. This zone of reflectors is not well imaged on the full-fold stack of Line 2 (Fig. 6) because of the crooked geometry of the seismic line. Reflections F do not migrate above reflections E; therefore, they appear to be confined to a block which is bounded above by reflections E and below by the Moho (reflections G and H, see below) (Fig. 5).

G and H are subhorizontal parallel reflections seen on all stacked sections at travel times of about 10 and 10.6 s, respectively (Figs. 5, 6, and 7). The depth to the reflectors which produced H corresponds to the depth to Moho (33–35 km) determined by seismic refraction surveys (Hill, 1972; Rohay, 1982). Reflections H are part of a regionally extensive set of

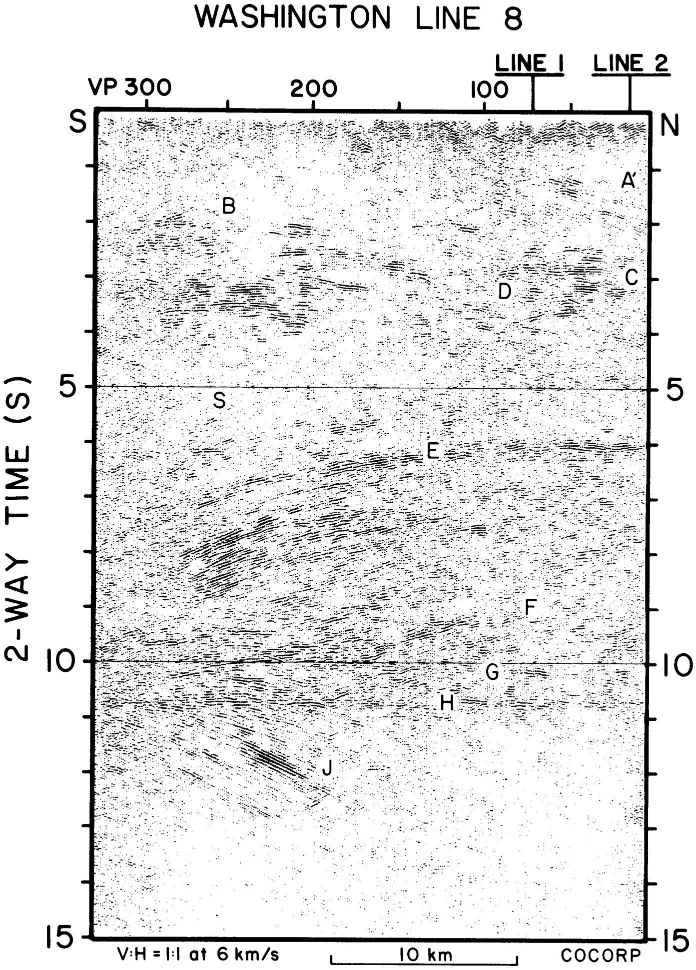

Figure 7. Unmigrated, coherency-filtered, full-fold, stacked section of Washington Line 8. Letters refer to reflection zones discussed in the text.

similar reflections which have been interpreted by Potter and others (1986) as the Moho. The 3-D data show that the Moho in this region is a nearly horizontal planar feature.

Reflections I, present on sub-lines 2B and 2C at travel times greater than that to the Moho (Fig. 5), are also seen on the full-fold stack of Line 2 where they dip easterly between 11 and 13 s (Fig. 6). These reflections have optimum stacking velocities of 2–4 km/s, which are much slower than would be expected from a dipping reflector in the lower crust or upper mantle. One possibility to explain these arrivals is that they are reflections (or "sideswipe") from a near-surface feature. Reflections I are enigmatic, but the low stacking velocities suggest that they are not from a deep crustal reflector.

On the southern end of the full-fold stack of Line 8, there are strong north-dipping reflections which also have travel times greater than that to the Moho (J; Figs. 7, 8, and 9). These reflections have stacking velocities of 7–9 km/s and appear to increase in dip with depth. There is no three-dimensional control on this part of Line 8. Conventional 2-D migration places these reflections above the Moho. The high stacking velocities suggest that these reflections are from a feature within the middle to lower crust rather than sideswipe from a near-surface feature. An extension of Line 8 to the south could possibly allow an interpretation of J to be made. Without 3-D control, however, no interpretation can presently be justified other than to say reflections J are from a steeply dipping structure in the lower crust beneath the Okanogan Dome.

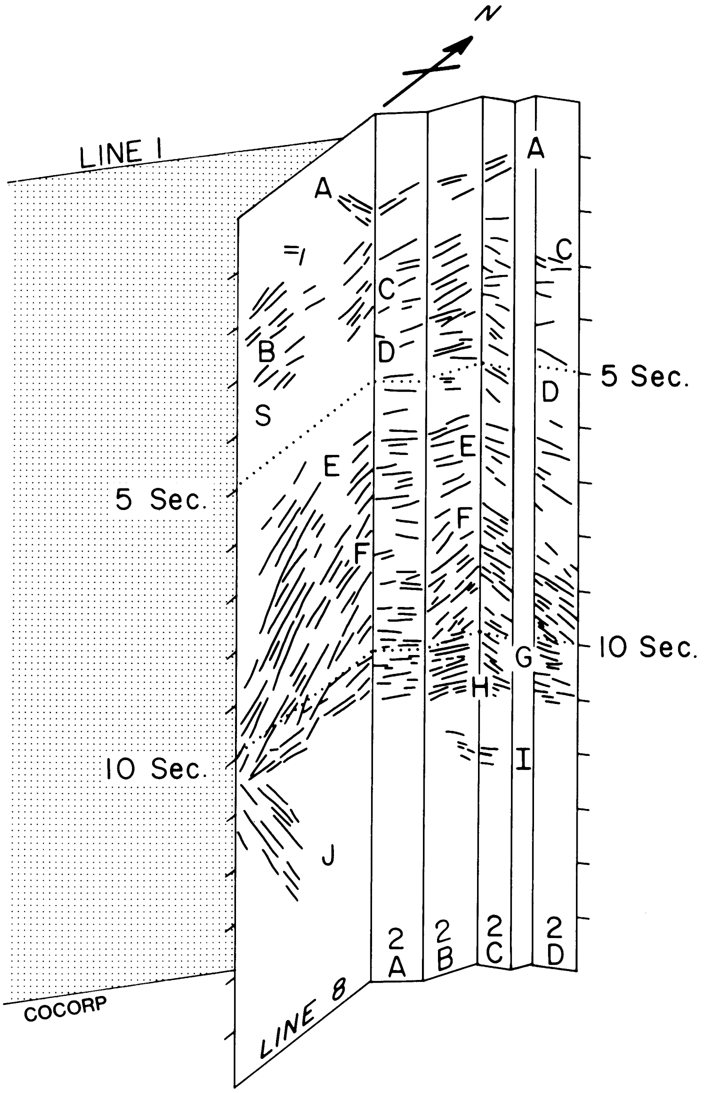

Figure 8. Perspective view of line drawings of unmigrated data from the four sub-lines and Washington Line 8. Letters refer to reflection zones discussed in the text. View to the northwest.

DISCUSSION

Interpretations of the seismic data described above are based upon reflector geometries and published local and regional geological and geophysical information. These interpretations have been used to construct a structural block diagram (Fig. 10) through the area of the seismic lines used in this study. The local surface geology is shown in Figure 10 along with the interpretations so one may see its relationship to the interpreted data.

The most widespread and continuous features in the deep crust seen on these data and those from the rest of the COCORP transect are reflections G and H (Figs. 6, 7, 8, and 9), which have travel times that correspond to the depth to Moho. G and H form a continuous series of horizontal reflections, above which the south-dipping reflections F terminate (Fig. 5). All reflections which occur at travel times greater than that to the Moho migrate to a position above the Moho. The regional persistence of strong Moho reflections defining a flat surface directly beneath complexly deformed crust and, in some places, truncating deep crustal features (this study; Potter and others, 1986) suggest that the flat Moho geometry formed late in the evolution of the orogen. The smooth Moho geometry was probably developed in Cenozoic time, perhaps during Eocene magmatism and extension because structures inferred to be Eocene extensional features appear to sole into the Moho beneath easternmost Washington (Potter and others, 1986). Reflections G, which are above and parallel to the Moho, are similar to features in Nevada COCORP data interpreted by Klemperer and others (1986). These reflections may represent the top of a transition zone from lower-crustal material to upper-mantle material, the bottom of this transition zone being the reflection Moho. The layered nature of the Moho reflections and the observation that they truncate south-dipping structures may also suggest that the Moho reflections represent an intrusive feature, a structural detachment, or both. The flat, laminar nature of the Moho may be a result of magmatic underplating and/or intrusion at the base of the crust or the Moho may have acted as a fault zone during Eocene extension which truncated older lower-crustal structures.

Reflections A and A′ (Figs. 5, 7, and 8) are the shallowest reflections clearly seen on the data. As mentioned earlier, reflections A′ project toward the surface to the location where Line 8 crosses the mapped edge of the Okanogan Dome, between orthogneisses to the south and the overlying low-grade Mesozoic and Paleozoic accreted rocks to the north (Figs. 2 and 10). Reflections A seen on Line 2 project over a distance 15 km, from a depth of 5 km, to a normal fault bounding the eastern side of the Toroda Creek Graben (Bodie Mountain fault; Pearson, 1967; Orr, 1985) (Figs. 2 and 10). The Bodie Mountain fault has a dip of 20°–25° to the west (Pearson, 1967) which corresponds well to the 18°–23° determined for A in this study. The Bodie Mountain fault separates amphibolite-grade rocks of the Tenas Mary Creek sequence (Cheney, 1980; Pearson, 1967; Orr, 1985) from the Paleogene fill of the Toroda Creek Graben. Therefore, A and A′ are interpreted as representing the contact between the high-grade metamorphic rocks and overlying rocks.

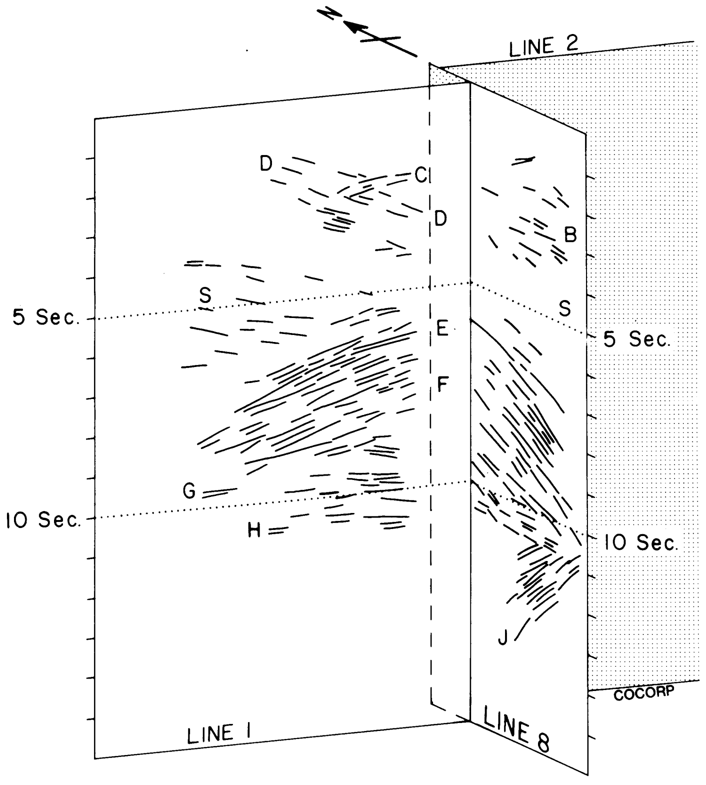

Figure 9. Perspective view of line drawings of unmigrated data from Washington Lines 1 and 8. Letters refer to reflection zones discussed in the text. View to the northeast.

The sense of relative motion between the orthogneiss of the Okanogan Dome and overlying accreted rocks is unknown. It is possible that this boundary may have been the thrust between the Intermontane Terrane and North America in Jurassic time. The K-Ar uplift ages, along with the juxtaposition of two such contrasting lithologies, however, suggest that its most recent movement may have been in a normal sense during Eocene uplift of the Okanogan Dome. If this is so, then reflections A and A′, which occur at the same travel times where Lines 2 and 8 intersect, may represent an undulatory detachment surface similar to the scoop-shaped Newport fault which straddles the Washington-Idaho border (Miller, 1971; Harms, 1982).

The geometries of reflections C (Figs. 5, 6, and 8) are suggestive of an imbricate fault geometry. These reflections are truncated on the west by the east-dipping reflections D, thereby suggesting that the structure which produced D is younger than the structures producing C. Potter and others (1986) have suggested that reflections D on Line 1 may be correlative with an east-dipping mylonite zone within the Okanogan Dome (Waters and Krauskopf, 1941; Fox and others, 1976), because they project toward the surface exposure of these mylonites (Fig. 2). The age and sense of displacement along the mylonite is not clear from the available geologic information. On the basis of the geometries seen on the reflection data, however, D may represent a down-to-the-east normal fault which has cut possible Mesozoic thrust-related structures (Figs. 2 and 10). Reflections D can be traced to at least 5 s (15 km) beneath the western end of Line 2 (Fig. 6). Geologic mapping has shown that the east-dipping mylonites intersect the west-dipping mylonites of the Okanogan Valley fault (Figs. 2 and 10). Because these east-dipping mylonites occur in the footwall block of the Okanogan Valley fault, it may be inferred that fault D is older and represents a deeper level than the Okanogan Valley fault. It must be stressed that there is little geological information available on these mylonites, and the ages of the rocks cut by the mylonites are uncertain; therefore, any interpretations made at this time are only tentative.

The structures imaged beneath the Okanogan Dome may be broadly analogous to those exposed in the Valhalla Complex in southeastern British Columbia (Fig. 1), where Carr and others (1987) have observed that the ductile Valkyr shear zone, which probably roots to the east, is cut by the east-dipping Slocan Lake fault zone, which is a ductile to brittle normal fault. Both of these faults are believed to have formed during progressive stages of Eocene extension (Carr and others, 1987). Beneath the Okanogan Dome, it is possible that fault D and the Okanogan Valley fault also formed during progressive stages of Eocene extension, with the ductile and brittle younger fault (Okanogan Valley fault) uplifting the deeper seated, ductile, slightly older fault (D) in its footwall. In the Okanogan Dome case, the seismic data suggest that the two faults have opposing dips in contrast to the subparallel dips inferred by Carr and others (1987) for the features in the Valhalla Complex.

The highly reflective crust beneath the Okanogan Dome is similar to the highly reflective crust seen beneath other core complexes, such as the

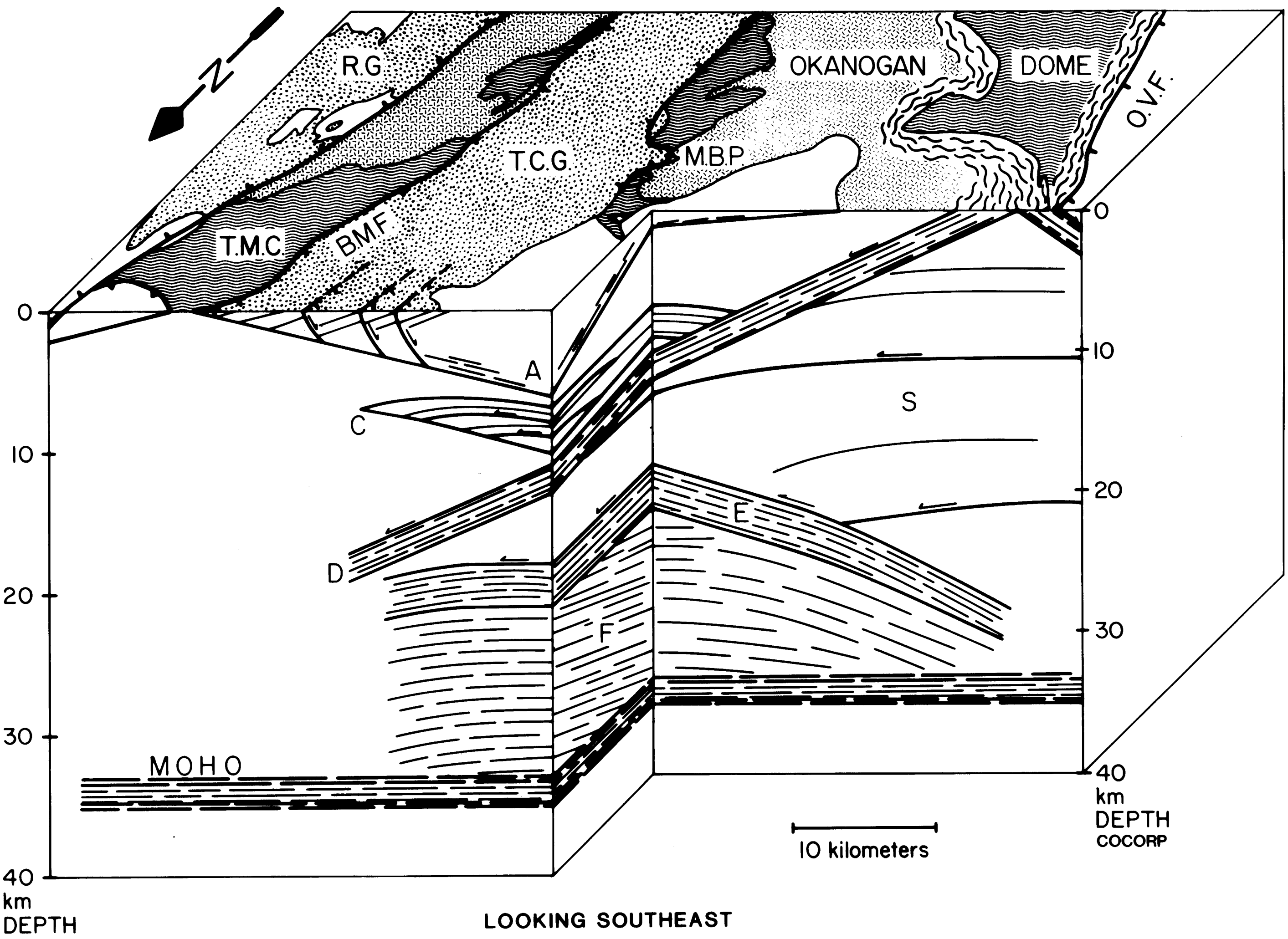

Figure 10. Block diagram illustrating the three-dimensional structure beneath the northern edge of the Okanogan Dome. The view in this figure is in the southeast. Map patterns are the same as in Figure 2. OVF: Okanogan Valley fault; TCG: Toroda Creek Graben. Structural data from this paper, Potter and others (1986), Orr (1985), Cheney (1980), Fox and others (1977), Waters and Krauskopf (1941), and Monger (1968).

Priest River Complex (Potter and others, 1986) and Kettle Dome (Hurich and others, 1985) in eastern Washington and the Picacho Mountains complex in Arizona (Reif and Robinson, 1981). The imbricated pattern of reflections C and similar patterns of reflections B seen beneath the Okanogan Dome on Line 8 (Figs. 7 and 8) may be interpreted either as being a result of Mesozoic compression, with each lens representing a thrust slice, or as lens-like extensional features similar to the suggestion of Hamilton (1982). Brown and others (1986) have suggested that thrusting in a duplex style has been responsible for most of the uplift of the Monashee Complex approximately 150 km to the north. Price and others (1981, 1985), Parrish and others (1985), and Journeay and Brown (1986) have emphasized the significance of crustal extension in southernmost British Columbia and northeastern Washington. Potter and others (1986) suggested that much of the extension in this region has been concentrated in discrete zones of shear which extend at least to the middle crust and feed into broad, dipping deformation zones in the lower crust. There is no strong evidence to rule out the possibility that some of the reflections seen beneath the Okanogan Dome represent structures related to distributed Eocene extension.

The most prominent features seen in the reflection data are reflections E and F and associated diffractions. The mid-crustal reflections E are discordant to east-dipping reflections above and south-dipping reflections below (Figs. 5, 6, and 7) and appear to define a major zone of discordance. E forms the upper bound to the zone of south-dipping reflections F, which are bounded below by the Moho (G and H). The structure producing reflections E strikes approximately parallel to structures in the thrust belt to the east and is 1–3 km thick. These characteristics are very similar to those of the Monashee Décollement (Brown and Read, 1983), and E is interpreted as a similar thick mid-crustal deformation zone (probably mylonitic) that was formed during northeastward-directed thrusting in the Mesozoic or early Paleogene.

Reflections F, which are confined to a block beneath E and truncated by E (Figs. 5, 7, 9, and 10), appear uniform in character. Reflections F, therefore, define a lower-crustal block of south-dipping structures which were formed previous to, or at the same time as, the mid-crustal thrust described above. The strong diffractions associated with these zones on Lines 1 and 8 may be due to the truncation of the south-dipping structures along a major ramp in the thrust structure represented by reflections E (Fig. 10).

There is a conspicuous zone of relatively few reflections, labeled zone S, between 4 and 6 s two-way travel time on Lines 1, 2, and 8 (Figs. 6 and 7). This zone is in contrast to the highly reflective zones above (B and C) and below (E and F). As the reflection character of zone S is quite different from the surrounding zones, S may represent a thrust slice of relatively isotropic rock (for example, a pluton, a high-grade metamorphic rock which has not developed a planar fabric, or a zone of nearly vertical foliations).

A possible interpretation is that S is a thrust slice that has been thrust over the lower-crustal zone F along fault E, producing a crustal-scale duplex structure (Fig. 10). The stacking of these thrust slices was responsible for the thickening of the crust and for much of the uplift of the amphibolite-grade rocks now exposed in the Okanogan Dome, following the style of uplift proposed for the Monashee Complex (Brown and others, 1986) (see Fig. 3). Thrusting continued in this region into Paleocene time (Price, 1981).

The lower-crustal zone F may represent Proterozoic rifted North American continental crust not disturbed during Phanerozoic deformation. The south-dipping reflectors may be, among other possibilities, rift-related structures or sheets of Precambrian granitic gneiss similar to those seen in the Thor-Odin nappe structurally beneath the Monashee Décollement in the Shuswap Complex (Duncan, 1984), or both.

Alternatively, it is possible that reflections F represent a south-dipping basement duplex structure formed along a lateral ramp, with the Moho as the floor thrust and E as the roof thrust. The south-dipping reflections could represent the faults of the duplex structure and/or imbricated layers within the thrust-bounded slices.

Divergence of Strikes of Thrust and Normal Faults

In this study, both Eocene normal faults and Mesozoic thrust faults have been interpreted. These interpretations have been based largely on the three-dimensional information provided by the sub-lines. The interpreted thrust faults strike northwest, and the normal faults strike north-south to northeast. The surface exposures of the major thrusts in the Shuswap Complex to the north and in the Rocky Mountain thrust belt strike northwesterly (Fig. 1). The normal faults exposed in the vicinity of the Monashee Décollement follow the northwest trend of the Mesozoic structures (for example, the Columbia River fault; Read and Brown, 1981; Journeay and Brown, 1986; Brown and Journeay, 1987). In the southern region of the Shuswap Complex, however, the structure is dominated by Eocene extensional features. The normal faults exposed here and those interpreted from the seismic data in this study strike north-south to northeasterly (Fig. 1) and apparently cut Mesozoic thrust structures. The divergence of normal-fault and thrust-fault strikes in this region requires that the normal faulting did not occur simply as gravitational relaxation along pre-existing thrust structures, as proposed for other Cordilleran core complexes by Armstrong (1982) and Coney and Harms (1984) and for the northern Shuswap Complex by Brown and Journeay (1987). Rather, the data imply that such effects were modified by changes in plate-boundary conditions at these latitudes (Engebretson and others, 1985) that resulted in the development of major transcurrent faults and contemporaneous crustal extension in the southern Omineca Belt (Price, 1985; Price and Carmichael, 1986).

Possible North-South Correlation of Structures

The relationships between the thrusts of the duplex structure beneath the Okanogan Dome to those beneath the Monashee Décollement are unknown. Down-plunge projection of major structures, such as the Monashee Décollement, within the Shuswap Complex suggests that one or more of these thrusts may be imaged beneath the COCORP lines. It is possible that reflections E are from a structure which is continuous with the basal thrust beneath the Monashee Décollement (Monger and others, 1985; Brown and others, 1986) and that the thrust separating zone S from the overlying reflections B represents a structure analogous to, or continuous with, the décollement itself. Alternatively, E may be continuous with the Monashee Décollement. If this is the case and the reflectors of zone F are a Proterozoic fabric, then the basement horses which form the duplex structure beneath the Monashee Décollement would have to die out along strike to the south. Otherwise, this can be explained if zone F is a Mesozoic duplex formed along a lateral ramp in the thrust system. The extension of Line 8 northward through Canada would provide information on the regional three-dimensional structure of the crustal duplex and on the relationships between deep thrust structure inferred here from seismic data and to the north from geological reconstructions.

CONCLUSIONS

By dividing a very crooked seismic line into short straight line segments, we have been able to determine the three-dimensional structure of the continental crust beneath the Okanogan Dome crystalline complex in north-central Washington. The results from this simple processing technique have provided constraints on the formation of the crystalline complex and on the general evolution of the crust in this region.

The main results are as follows:

1. Dramatic vertical variation in structural orientation occurs in the crust in this region, as might be expected in other areas which have a complex orogenic history.
2. A block of south-dipping structures has been identified in the lower crust which may represent either the Proterozoic rifted margin or older basement of North America or a Mesozoic duplex structure which formed along a lateral ramp.
3. A zone of prominent reflections interpreted as a mid-crustal thrust overlies the block of south-dipping structures. This thrust at 20 km depth may be the basal thrust of a crustal-scale duplex which accommodated northeasterly directed thrusting during Mesozoic-Paleocene convergence. The thrusts of the duplex may be continuous with those of an analogous proposed duplex beneath the Monashee Décollement (Monger and others, 1985; Brown and others, 1986) and possibly with the Monashee Décollement itself, suggesting that the extension of the seismic traverse northward may trace a deep crustal feature to the surface.
4. A series of east-dipping reflections project into mylonites exposed in the western part of the Okanogan Dome. These reflections can be traced into the mid-crust and possibly represent a normal fault which is older than the Eocene Okanogan Valley fault, which bounds the western edge of the dome.
5. Beneath this complexly deformed crust, the Moho is a regionally planar feature and truncates lower crustal structure. The present configuration of the Moho is probably Eocene or younger in age (this study; Potter and others, 1986).
6. The seismic data support the idea that the southern Omineca Belt underwent crustal thickening and uplift during Mesozoic to Paleocene convergence, which was responsible for the high-grade metamorphism, followed by final uplift and exposure during Eocene extension and magmatism (Okulitch, 1984).

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