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COCORP DEEP SEISMIC REFLECTION TRAVERSE OF THE INTERIOR OF THE NORTH AMERICAN CORDILLERA, WASHINGTON AND IDAHO: IMPLICATIONS FOR OROGENIC EVOLUTION

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Abstract. Deep seismic reflection data collected by the Consortium for Continental Reflection Profiling along a transect of the interior of the northwestern U. S. Cordillera indicate the presence of crust-penetrating faults; these faults developed during an orogenic cycle consisting of Jurassic to Paleocene accretion-related crustal thickening followed by Eocene crustal thinning. The reflection data also suggest that the Moho is a young, dynamic feature which developed a relatively smooth, flat geometry beneath a complexly deformed crust, probably during an Eocene episode of crustal extension. The profiles reveal prominent west dipping reflection sequences (and associated diffractions) interpreted as a Mesozoic thrust system of crustal dimensions that linked accretion-related shortening in the western Cordillera with the thrust belt in the eastern Cordillera, east dipping reflections that crosscut the west dipping reflections in the middle and lower crust and are interpreted as ductile deformation zones that accommodated Eocene crustal extension, and essentially flat Moho reflections at 33-35 km beneath complexly deformed crust. These features are consistent with a sequence of (1) late Mesozoic crustal imbrication of transitional crust beneath the easternmost accreted terrane which overrode the North American passive continental margin along a Jurassic thrust (2) propagation of crust-penetrating thrusts to shallower levels in the east, where they probably formed the sole of the Rocky Mountain Thrust Belt (3) Eocene extension that disrupted these thrusts and led to uplift of core complexes along detachments which fed into broad deformation zones in the lower crust and (4) development of a flat Moho geometry during Cenozoic extension and magmatism. These data provide new information about the structure of the entire crust in the Cordilleran interior and offer a working model, both for evolution of Cordilleran core complexes and possibly for other collisional orogens.

INTRODUCTION

Knowledge of the deep structure underlying the interior of mountain belts, which contain exposures of rocks deformed and metamorphosed at deep crustal levels, is essential to an understanding of orogenic evolution. In the North American Cordilleran interior, polydeformed metamorphic uplifts ("core complexes" [see Crittenden et al., 1980; Armstrong, 1982]) developed largely or entirely within North American basement between the thin-skinned

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fold and thrust belt and the "accreted terranes" [Coney et al., 1980; Monger et al., 1982]. The metamorphic rocks of the interior have undergone major uplift during both Mesozoic shortening and Tertiary extension [Coney and Harms, 1984; Price, 1979, 1985; Journeay and Brown, 1986]. The crust both west and east of the core complexes has experienced large horizontal displacements, and therefore these exposures of midcrustal rocks offer a key to the understanding of deep-seated shortening in orogenic belts. However, little is known about the detailed mechanisms of crustal shortening beneath this region. Similarly, mechanisms for crustal scale Tertiary extension of tectonically thickened crust are not well known [Armstrong, 1982; Coney and Harms, 1984]. A recently compiled crustal cross section through the Cordillera at the latitude of this study [Cowan and Potter, 1986], based mainly on surface geologic constraints, illustrates Mesozoic shortening and Cenozoic extension in the middle and deep crust in a quite schematic fashion, further emphasizing the lack of detailed information on these processes.

Consortium for Continental Reflection Profiling (COCORP) deep seismic reflection profiles in the Cordilleran interior of northeastern Washington and northern Idaho suggest that Mesozoic thrust imbrication at deep crustal levels led to thickening of the crust in the interior, similar to the crustal duplex models proposed for the Shuswap Complex (250 km along strike to the north) by Monger et al. [1985] and Brown et al. [1986]. This thrust geometry was disrupted by Eocene normal faults inferred from the COCORP data and documented by geologic studies [Price, 1979; Ewing, 1980; Rhodes and Cheney, 1981; Fox and Beck, 1985; Price et al., 1985]. The COCORP data suggest that moderately dipping Eocene detachments, which accommodated extension in the upper crust, passed into broad ductile deformation zones in the middle and lower crust. Dipping reflections interpreted as deep crustal Eocene deformational fabric cut inferred thrusts and appear to sole into strong, flat Moho reflections, suggesting that normal sense displacement along these dipping zones was accommodated laterally along the Moho. The COCORP profiles are thus consistent with an evolutionary cycle of crustal thickening followed by crustal extension, and they serve as a crustal scale example of similar cycles documented in many metamorphic core complexes of the North American Cordillera [Armstrong, 1982; Coney and Harms, 1984]. Deep seismic reflection profiling of the Cordillera by Canadian scientists just north of the Canada-U.S. border [Price et al., 1986] and proposed long cross lines linking the data reported in this paper with seismic profiles in Canada should provide further constraints on these models.

REGIONAL TECTONIC SETTING

The COCORP lines form an east-west transect across exposures of the metamorphic core complexes and the easternmost accreted terrane (Intermontane Terrane [Price et al., 1985]), which was thrust as a thin sheet in early Jurassic time over the rifted edge of Proterozoic and Paleozoic North America [Brown and Read, 1983; Archibald et al., 1983; Monger, 1984; Okulitch, 1984]. The Kootenay arc (Figure 1) is a complexly deformed, arcuate zone across which great structural relief occurs; the westernmost known North American Proterozoic and Paleozoic sedimentary sequences and the easternmost accreted Mesozoic and Paleozoic rocks occur along the Kootenay arc. It is inferred to mark the position of a major basement step generated during Proterozoic rifting, which later served as a significant ramp during late Mesozoic and earliest Tertiary thrusting [Price, 1981]. The three large metamorphic complexes in the region (Figure 1) contain high-grade gneisses of probable or proven Precambrian age. East of the Kootenay arc, the Priest River Complex contains Proterozoic sillimanite- and kyanite-bearing gneisses [Clark, 1973; Rhodes and Hyndman, 1984]. The Okanogan and Kettle Dome metamorphic complexes lie west of the Kootenay arc and east of the western edge of continental crust, inferred from initial $^{87}Sr/^{86}Sr$ ratios [Armstrong et al., 1977]. Both metamorphic complexes contain rocks lithologically and isotopically very similar to Proterozoic gneisses of the Priest River Complex [Cheney, 1980; Orr, 1985b; R. L. Armstrong, personal communication, 1985]. The areas flanking the metamorphic complexes are characterized by thick sequences of Eocene volcanic and nonmarine sedimentary rocks. Adjacent to the Kettle and Okanogan domes, the Eocene rocks were deposited on weakly metamorphosed Paleozoic and Mesozoic arc-related rocks (part of the Intermontane Terrane) [Price et al., 1985] which had been thrust over the basement rocks, probably in Jurassic time [Okulitch, 1984; Orr, 1985a, b]. No strata with unequivocal North American pre-Terti-

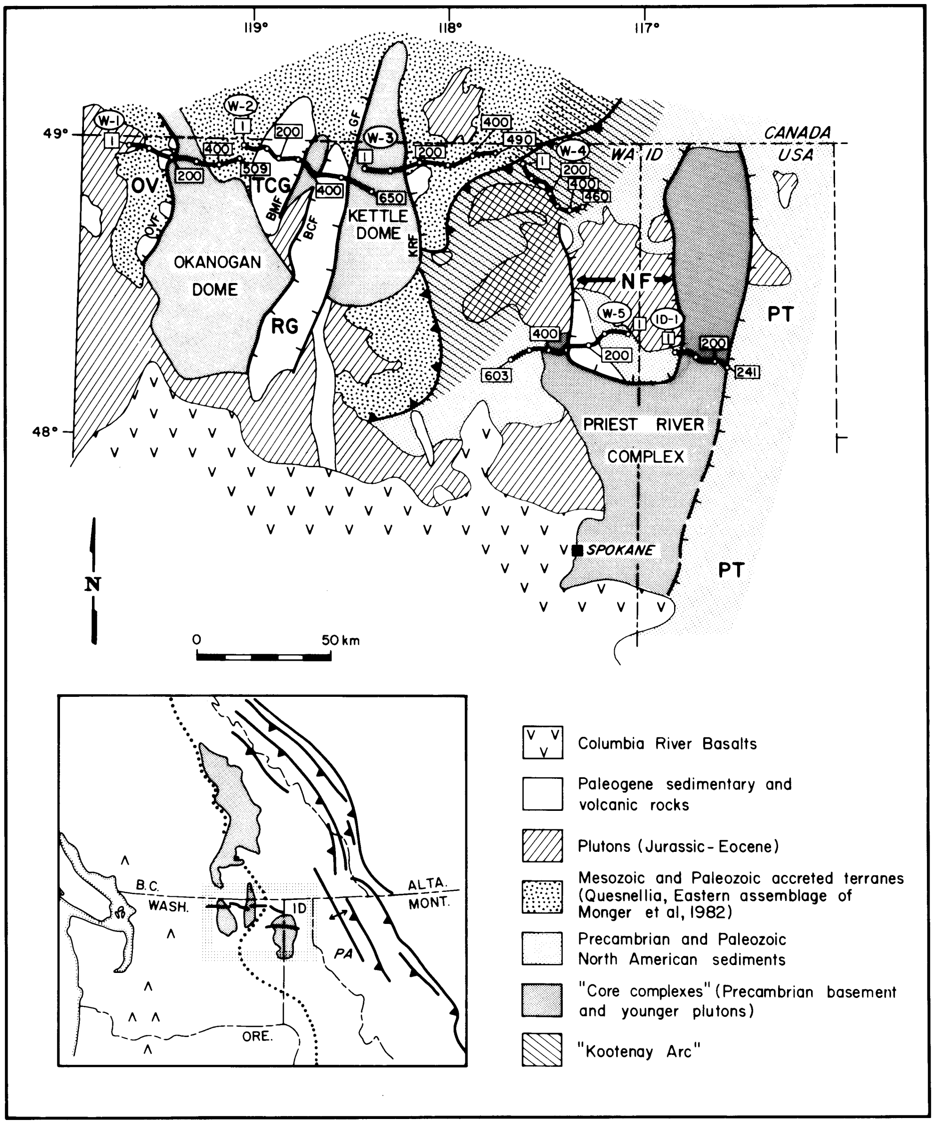

Fig. 1. Location and geologic setting of the COCORP deep seismic reflection lines discussed in this paper. W-1, W-2, W-3, W-4, and W-5 refer to COCORP Washington lines 1-5; I-1 refers to COCORP Idaho line 1. Numbered boxes refer to station numbers (vibration points) on COCORP lines. OV, Okanogan Valley; TCG, Toroda Creek Graben; RG, Republic Graben; KRF, Kettle River fault; NF, Newport fault; PT, Purcell Trench; BCF, Bacon Creek Fault; GF, Granby fault; BMF, Bodie Mountain fault; KRF, Kettle River fault. Inset is index map showing the location of the seismic lines with respect to major features of the Cordillera. Stippled box is the area shown on the detailed location map. S, Shuswap Complex; PA, Purcell Anticlinorium; dotted line represents the approximate eastern limit of accreted terranes mapped at the surface.

ary affinities are found immediately adjacent to the Okanogan and Kettle domes. Adjacent to the Priest River Complex (structurally above the Newport fault), Eocene sedimentary and volcanic rocks were deposited on the North American Proterozoic Belt Supergroup [Miller, 1971; Harms, 1982].

These metamorphic complexes clearly contain deformation zones recording Mesozoic thrusting [Orr, 1985a, b; Rhodes and Hyndman, 1984; Parrish et al., 1985] and are bounded by Eocene normal faults recording both ductile (mylonitic) and brittle deformation [Rhodes and Cheney, 1981; Harms, 1982; Harms and Price, 1983; Parrish et al., 1985; Tempelman-Kluit and Parkinson, 1986]. The complexes were rapidly uplifted in Eocene time, based on K-Ar cooling ages in hornblende and biotite within the crystalline rocks [Miller and Engels, 1975; Fox et al., 1977]. In summary, this was an area of Eocene extension, volcanism, and uplift of metamorphic complexes which had experienced an earlier thrust-related deformation, features similar to other metamorphic core complexes exposed at similar positions along strike in the North American Cordillera north of southernmost Nevada [Armstrong, 1982; Crittenden et al., 1980].

Important unresolved issues related to deep crustal structure of this critical hinterland area include the configuration and kinematics of structures related to both Mesozoic shortening and Eocene extension. How are the large Mesozoic displacements that are documented in accreted terranes of the western Cordillera accommodated beneath the uplifted basement terranes of the interior? Is there a traceable link between accretion-related structure to the west and thrust belt imbrication to the east? Eocene extension of overthickened crust closely followed thrusting; how was this accomplished on a crustal scale?

COCORP DATA

Six seismic reflection lines (Washington lines 1-5 and Idaho line 1, Figure 1) with a total length of 296 km were acquired by COCORP in 1984 and form the initial part of a planned cross-Cordilleran transect at 48°-49°N latitude. These data were collected using the Vibroseis (registered trademark CONOCO, Incorporated) technique to produce a correlated record length of 16 s. This two-way travel time corresponds to a maximum depth of about 50 km. The data processing sequence consisted of amplitude normalization, deconvolution, trace editing, velocity analysis, normal moveout corrections, muting, datum and residual static corrections, and stacking; a series of constant velocity migrations of line drawings were generated for all of the stacked data.

Figure 2 summarizes the data in line drawing form, showing unmigrated reflection patterns, migrated reflection patterns, and our interpretation. Examples of data from individual seismic lines are shown in (Figures 3-6). Dipping reflections are apparent throughout the transect; in places, these are accompanied by strong diffractions which collapse upon migration. Prominent west dipping reflection sequences occur in the middle to deep crust in the western part of the transect and at progressively shallower levels in more easterly parts of the transect. Shallow east dipping reflections also occur locally. Moderately to gently east dipping reflections in the deep crust in the eastern part of the transect cut across trends defined by structurally higher west dipping reflections. Prominent flat reflections occur at two-way travel times appropriate for Moho depths, with horizontal reflections developed locally above them.

The paneled nature of the seismic data along the transect is also evident from Figure 2. Some panels of data contain many reflections, while others are nearly reflection-free. The areas with fewer reflections correspond to areas where cultural and environmental noise (highway traffic, logging operations, noisy streams) was a problem during data acquisition. Hence the paneled nature of the data is considered to be due to surface conditions rather than to lateral geologic variations.

West Dipping Reflection Sequences

The major west dipping sequences, labeled A-E on Figure 2, occur at two-way travel times of 4.0-8.5 s (12-26 km) in the area west of and including the Kootenay arc (A, B, and C) and 1.2-4.0 s (3.5-12 km) east of the Kootenay arc (D and E). The major west dipping sequences are discussed below, from west to east.

Sequence A (Figures 2 and 3) lies beneath the east end of Washington line 1 and the west end of Washington line 2, northeast of the main exposure of Okanogan Dome. This sequence contains a prominent set of reflections and diffractions in a zone 1.0-1.5 s thick. Its upper bound occurs at travel times of 6 s (east end) to 7 s (west end); its lower bound extends to travel times of 8 s beneath the west end of the sequence (Figure 2a). After migration (Figure 2b) the arcuate diffractions at the west end of A collapse, and A consists of west dipping reflection segments which persist to depths of over 25

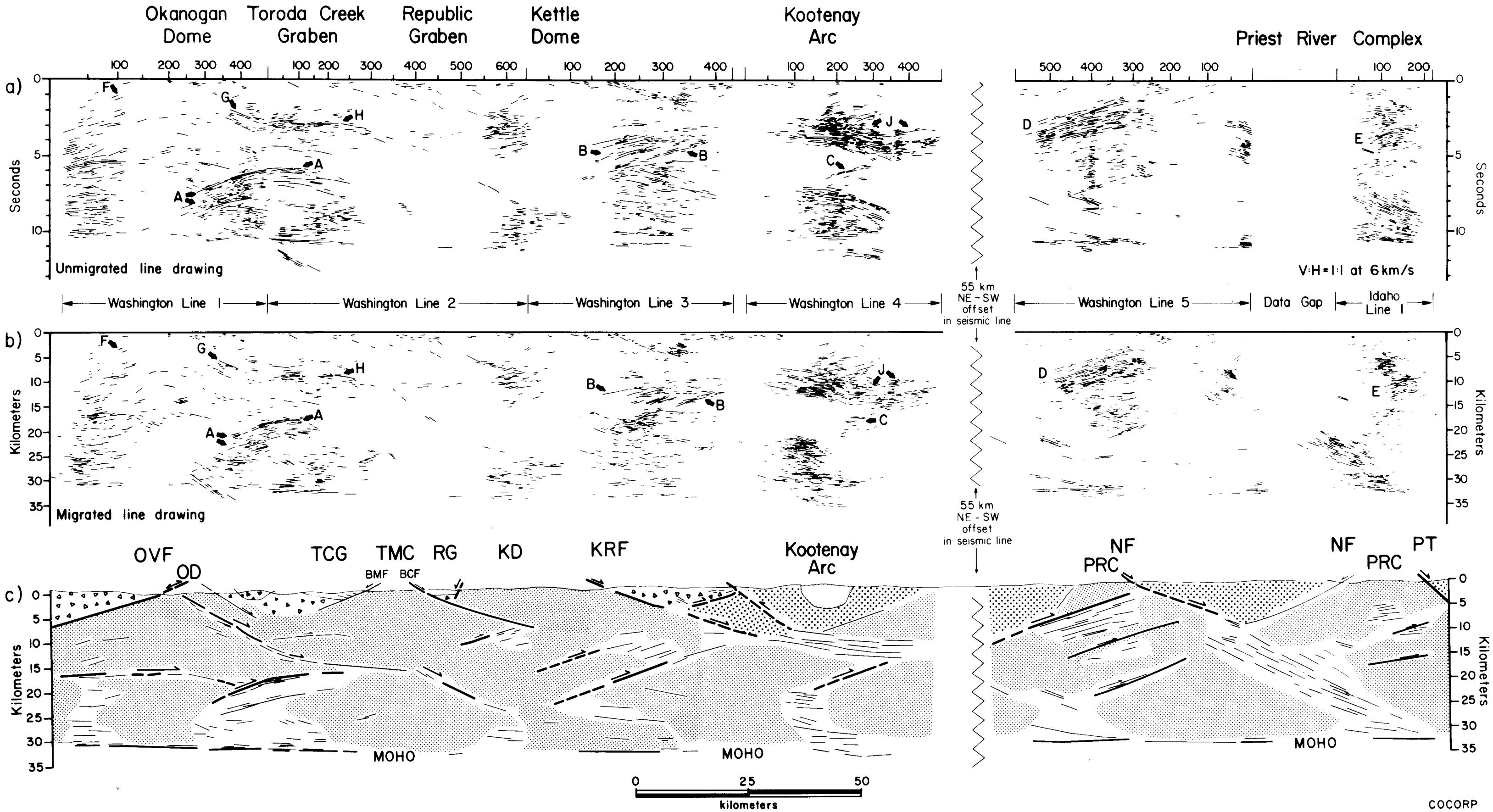

Fig. 2. Summary of data collected in the Cordilleran interior, Washington and Idaho during the summer of 1984. (a) Line drawings of all seismic sections discussed in text. Data are unmigrated, and the drawings are scaled so that H=V for a velocity of 6.0 km/s. (b) Migrated line drawings, produced by applying a migration routine to the line drawings shown in Figure 2a. The migration velocity used was 6.0 km/s. (c) Geologic interpretation of the seismic sections. This section incorporates the reflection data and surface geology into a model for crustal structure. Major features include west dipping Mesozoic thrust structures, traceable to depths of 23 km beneath the Okanogan dome, and shallowing to 5 km beneath the Priest River Complex; Eocene normal fault zones traceable to midcrustal depths, and interpreted to feed into broad lower crustal dipping deformation zones that sole into the Moho; and a relatively flat Moho geometry which is probably a product of Eocene extension and magmatism. Refer to text for discussion of rationale for the interpretations shown. Stipple pattern, sialic basement; dot pattern, Proterozoic and Paleozoic North American supracrustal rocks; random triangle pattern, Intermontane accreted terrane; diagonal ruled pattern, spirit pluton; OVF, Okanogan Valley fault; OD, Okanogan Dome; TCG, Toroda Creek Graben; BCF, Bacon Creek fault; BMF, Bodie Mountain fault; TMC, Tenas Mary Creek rocks; GF, Granby fault; KD, Kettle Dome; KRF, Kettle River fault; PRC, Priest River Complex; NF, Newport fault; PT, Purcell Trench.

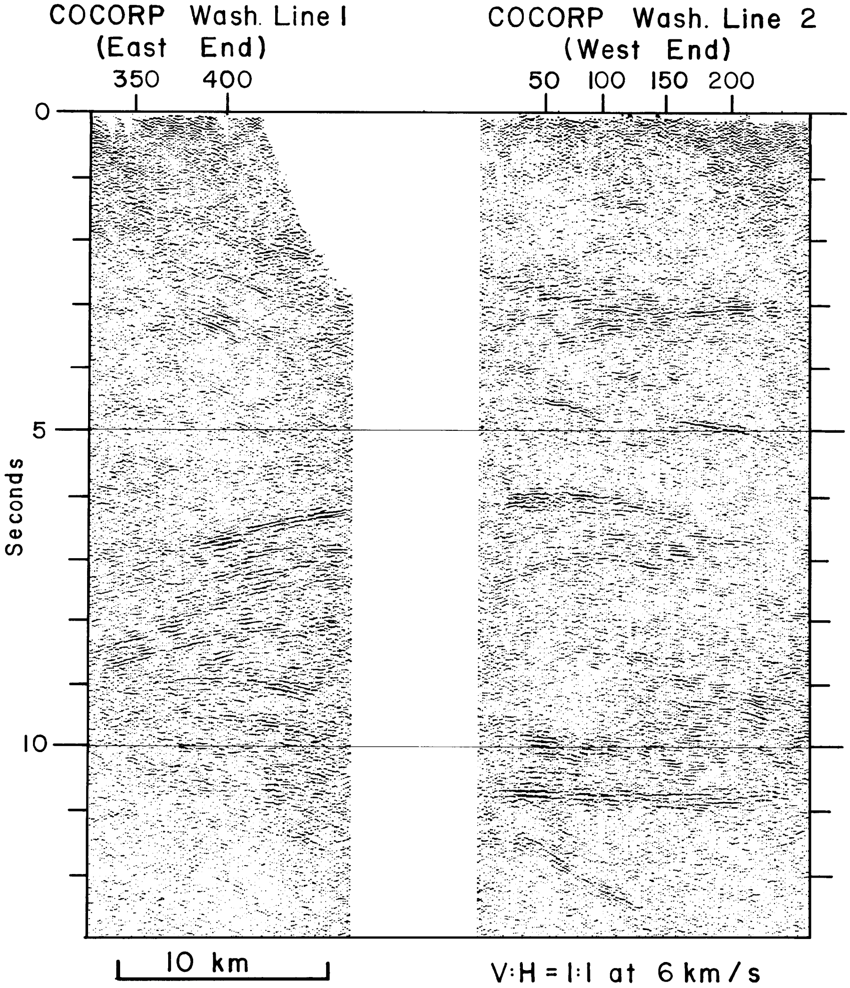

Fig. 3. Example of coherency-filtered unmigrated seismic sections from east end of COCORP Washington line 1 and west end of COCORP Washington line 2, NE of Okanogan Dome, near Chesaw, Washington. See Figure 1 for line locations. Numbers at top of the section refer to surveyed vibration points (stations). Spacing between successive stations is approximately 100 m. Vertical scale is two-way travel time. Features discussed in text include dipping reflections at 2-4 s which may represent a mylonitic zone mapped in the Okanogan Dome, prominent reflections and diffractions at 6-9 s which are interpreted as a mid crustal mylonitic thrust zone, and prominent horizontal Moho reflections beneath Washington line 2 at 10.8-11.0 s.

km, merging in the updip direction with flatter segments to the east at depths of about 18-20 km. Reflection sequence A is discordant with reflections that have an easterly apparent dip and terminate both above and below A. Detailed study of the three-dimensional geometry of deep reflections in this area [Sanford, 1986] defines several zones of alternately flat and dipping reflections in the middle and lower crust and shows that the upper and lower bounds of reflection sequence A are the principal zones of discordance.

Several west dipping reflections occur at two-way travel times of 2.5-3.5 s beneath the west flank of Kettle Dome on the east end of Washington Line 2 (vibration points (VPs) 550-650, Figure 2a). Immediately east of the surface exposure of Kettle Dome, reflection sequence B (Figure 2a) is defined by several straight, west dipping reflections on

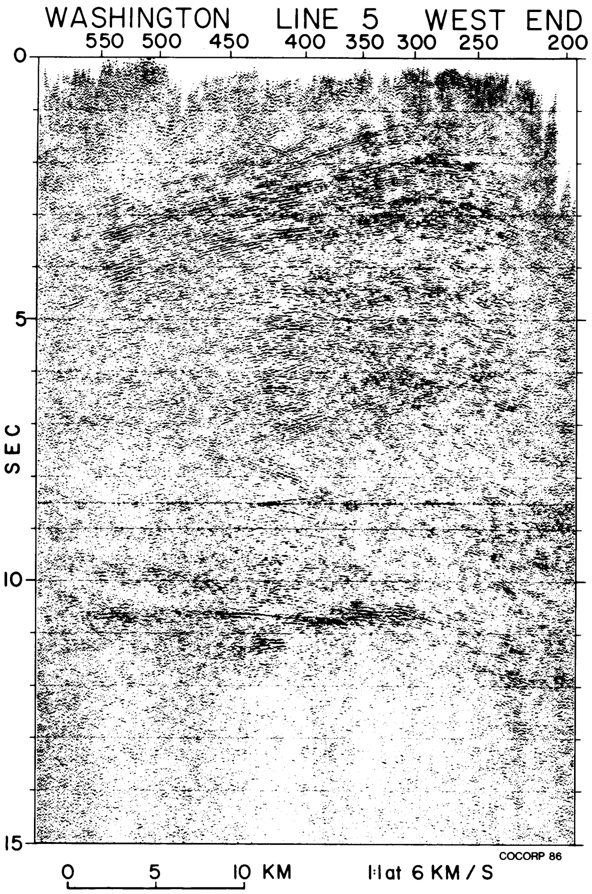

Fig. 4. Example of coherency-filtered unmigrated seismic section from west end of COCORP Washington line 5 east of Chewelah, Washington. See Figure 1 for line locations. Numbers at the top of the section refer to surveyed vibration points (stations). Spacing between successive stations is approximately 100 m. Vertical scale is two-way travel time. Features discussed in text include prominent dipping reflections at 1.0-4.5 s which are interpreted as a basement-transporting thrust, crossing east and west dipping reflections at 6-9 s, and strong Moho reflections at 10.6-11.0 s.

Washington line 3 (VPs 150-375) between 4 and 6 s. The migrated dip of these reflections is approximately 15°, and these reflections migrate to depths of about 10-17 km beneath VPs 175-475 (Figure 2b).

West dipping events C (beneath the Kootenay arc on Washington line 4, Figure 2a) consist mainly of diffractions, which seem to originate from the west end of a short west dipping reflection segment located at about 6 s beneath VPs 240-250. This short west dipping reflection segment occurs between gently east dipping reflection sequences in the upper crust (1.0-4.5 s) and lower crust (7.0-11.5 s).

Sequence D forms a broadly arcuate convex upward west dipping zone of reflections beneath the Priest River Complex and Kootenay arc on Washington line 5 (Figures 2 and 4). Two-way travel times to the top of sequence D (Figure 4) are 1.2-4.0 s (3.5-12 km), and the sequence is 1-2 s thick. This gently dipping sequence lies beneath complexly deformed, steeply dipping surface exposures, suggesting that a zone of decoupling lies at or above the top of sequence D. In addition, the shallowest part of D (Figure 4) consists of a set of west dipping reflections (1.2-1.6 s at VP 275; 1.9-2.3 s at VP 400) which are discordant with respect to deeper parts of sequence D. Beneath the prominent arcuate west dipping band of reflections in sequence D the middle crust contains lower-amplitude, consistently west dipping reflections down to two-way travel times of approximately 7.5 s beneath VP 400 and 7 s beneath VP 275.

Event E consists of a long diffraction originating from a short west dipping reflection segment at about 3 s travel time beneath the east part of the Priest River Complex on Idaho line 1 (Figure 2a) and lies within a west-dipping and subhorizontal reflection sequence from about 1.5 to 5.0 s.

Most of the major west dipping reflection sequences and events described above define zones of discordance; west dipping reflections cut across the trend of shallower (and some deeper) reflections or, in the case of D, are markedly discordant with respect to the steeply dipping surface structure 5-10 km above. For this reason, we interpret west dipping faults to be present along the top of, or above, these zones. The west dipping zones occur at middle to deep crustal levels across the entire orogenic interior and also in the shallow crust east of the Kootenay arc. This pattern fits with the inference of Price [1981] that the Kootenay arc served as a major ramp during thrusting and suggests that the west dipping reflections represent the deep westward continuation of the Rocky Mountain Thrust Belt system. The west dipping reflectors themselves can be interpreted as a deformational fabric within thick ductile fault zones in basement rocks, or as reflections from within overridden metamorphic sequences, or both (see discussion section). The position of major west dipping reflection sequences beneath and just east of the surface exposures of major metamorphic complexes suggests that ramping along Mesozoic and Paleocene basement-cutting thrusts was an important contributing factor in the uplift of these complexes. However, Mesozoic uplift apparently did not bring these rocks above the isotherms corresponding to K-Ar blocking temperatures in hornblende (450°-500°C) and biotite (250°C); they were uplifted through these isotherms in Eocene time [Miller and Engels, 1975; Fox et al., 1977].

Shallow Crustal Reflections

Upper crustal reflections not part of the pattern of west dipping reflections described above are discussed below, from west to east across the transect.

In the upper 3 s of the western part of Washington line 1 (VPs 1-125) there are several low-amplitude west dipping reflections (F on Figure 2) which overlie a reflective crustal section, consisting of alternating west dipping and subhorizontal zones, between 3 and 11 s. Beneath the east flank of the Okanogan Dome and the Toroda Creek Graben (east end of Washington line 1, west end of Washington line 2), prominent east dipping reflections are present (G on Figure 2a, at 2 s two-way travel time beneath VP 350 on line 1, to 5 s beneath VP 225 on line 2). There is also a horizontal reflection (H on Figure 2a) at 3 s on line 2, beneath VPs 1-210, with east dipping diffractions extending to VP 350.

Some of these shallow reflections may be from the Mesozoic and Paleozoic arc-related sequence (Anarchist Group, etc., part of the Intermontane Terrane [Price et al., 1985]) exposed around the flanks of Okanogan dome, or from the underlying thrust along which these rocks were abducted. These rocks and the Jurassic(?) thrust structures which affect them are highly folded [McMillen, 1979; Okulitch, 1984], however, and probably would not give rise to continuous reflections such as G and H. Based on their position and orientation, reflections F are more likely related to the broad west dipping mylonitic zone beneath the Okanogan Valley fault [Tempelman-Kluit and Parkinson, 1986]. G projects into the crystalline rocks of the Okanogan Dome and is probably correlative with a broad east dipping mylonitic zone mapped there [Fox et al., 1977; Waters and Krauskopf, 1941]. A detailed study by Sanford [1986] suggests that G continues into the prominent, gently east-dipping reflection beneath H at 4-5 s (Figures 2a and 3). H may be a splay of this zone or an older structure truncated by the mylonitic zone. It is not clear from geologic data whether this mylonitic zone marks a Mesozoic thrust, an Eocene normal fault, or both.

Gently east dipping reflections at 0-2 s between VPs 200 and 370 on Washington line 3 project to the surface location of the gently east dipping Kettle River fault and are interpreted as this Eocene normal fault. The reflections dip about 12°E, similar to reflections from the Kettle River fault seen on a short seismic line 35 km to the south described by Hurich et al. [1985].

A high-amplitude reflection sequence (J, Figure 2a) at 2.0-4.5 s two-way travel time beneath the western part of the Kootenay arc on Washington line 4 (VPs 125-325) has a SE apparent dip on the part of the seismic line oriented NW-SE. This sequence can be traced into a less obvious but persistent reflection sequence at 3-4 s on the NE-SW trending part of Line 4, between VP 325 and VP 464, which has a SW apparent dip. These relationships provide three-dimensional control, indicating that sequence J has a gentle southerly or southeasterly dip. Events with NW apparent dips intersect reflections J at 2.0-3.2 s between VPs 200 and 300, and other NW dipping events occur above J (1.2-2.5 s) between VPs 150 and 250. Since gently dipping reflections J lie beneath an area where the surface geology consists of complexly deformed, steeply dipping Paleozoic strata intruded by Cretaceous plutons, there is probably a zone of decoupling between the earth's surface and J. This zone of decoupling may lie along the top of J and could be a detachment accommodating displacement along west verging Mesozoic thrusts that strike NE along the Columbia River near Northport, Washington [Yates, 1971]. The reflections from the Kettle River fault on Washington line 3 also project toward J, so J may be a major Eocene extensional detachment which surfaces as the Kettle River fault and underlying mylonites.

Gently east dipping reflections at

0.3-0.5 s beneath VPs 260-270 on Washington line 5 project toward the mapped trace of the Newport normal fault at about VP 285 (Figures 1 and 2) and are interpreted as fault plane reflections. Weak reflections from the fault may continue to 1.0 s (1.5 km) beneath VP 230. Projecting this trend downdip, these reflections may correlate with east dipping reflections from 2.5 to 5.0 s beneath the east end of Washington line 5 (VPs 1-80, Figure 2), where surface exposures are part of the upper plate of the Newport low-angle normal fault (Figure 1). The uppermost of these east dipping reflections at 2.5-3.0 s (VPs 80 to 1) is interpreted as the Newport fault, since it directly underlies a series of west dipping reflections which are probably correlative with west dipping strata in the upper plate of the Newport fault. The east dipping reflections at 2.5-5.0 s project toward an east dipping reflection sequence in the lower crust beneath Idaho line 1 (Figure 2b).

Lower Crustal East Dipping Reflections

East of the Kettle Dome (Washington lines 3-5 and Idaho line 1, Figure 2), the lower crust (travel times 6.0-10.5 s) is dominated by east dipping reflections. On Washington line 3, between VPs 200 and 375, short subhorizontal and gently east dipping reflections are present persistently from 5.5 to 10.5 s beneath west dipping reflections B. On Washington line 4, east dipping features in the lower crust are probably diffractions (because they collapse upon migration) which may originate at the east end of a subhorizontal reflection sequence at 7-11 s beneath VPs 100-200. Beneath Washington line 5 and Idaho line 1 the migrated positions of east dipping lower crustal reflections cut across the trends defined by middle and upper crustal west dipping reflection sequences (Figure 2b). On these two seismic lines, the east dipping lower crustal reflections have progressively gentler dips with increasing depth, eventually becoming parallel to, or merging with, horizontal Moho reflections. Some examples of these relationships follow.

Beneath the west end of Washington line 5 (Figures 4 and 5), east dipping reflections between 7 and 9 s two-way travel time intersect west dipping reflections beneath VPs 400-450. Migration separates the east from west dipping reflections (compare Figures 2a and 2b); the migrated east dipping reflections form a panel in which reflections dip about 20°E and cut across the projected trend of the west dipping reflection sequence which occupies the middle and upper crust (4-24 km, Figure 2b). A gently east dipping reflection at 9.8-10.6 s (Figure 5) merges with Moho reflections at 10.6 s. This relationship still holds after migration, as shown by the migrated line drawing (Figure 2b). Similar features occur beneath Idaho line 1 (Figure 6), where east dipping reflections between 7.0 and 10.5 s have progressively gentler dips as Moho depths are approached, so that the deepest east dipping reflections are subparallel to, but do not intersect, the Moho.

Moho Reflections

Strong horizontal reflections occur at 10.5-11.0 s beneath a reflective lower crust on Washington lines 1, 2, and 5 and Idaho line 1. These travel times are appropriate for Moho reflections based on calculations of the depth of the Moho in this region from refraction studies (30-35 km [Hill, 1972; White et al., 1968; Rohay, 1982]). Few reflections occur beneath these features, which are similar in character to the "reflection Moho" seen on seismic data from other areas, such as the Nevada portion of the COCORP 40°N Cordilleran transect [Klemperer et al., 1986]. For these reasons, these strong reflections are interpreted as the Moho. They typically consist of a high amplitude two- or three-cycle event, about 0.1 s in duration (Figures 3, 5 and 6) and are typically bounded above by dipping reflections. Sanford [1986] demonstrated that a thicker zone of subhorizontal Moho reflections (1 s thick) beneath the western part of Washington line 2 is directly overlain by gently south dipping reflections. As discussed above, Moho reflections on Washington line 5 and Idaho line 1 are directly overlain by reflections with apparent gentle easterly dips (Figures 5 and 6). On Washington line 5 a gently east dipping reflection merges with the Moho reflection. Where Moho reflections are well developed, there are generally no deeper reflections seen. An exception occurs on Washington line 5 beneath VPs 420-450, where a gently west dipping reflection sequence occurs at travel times of 10.7-11.4 s immediately below Moho reflections at about 10.6-10.7 s. The east dipping reflection which occurs at

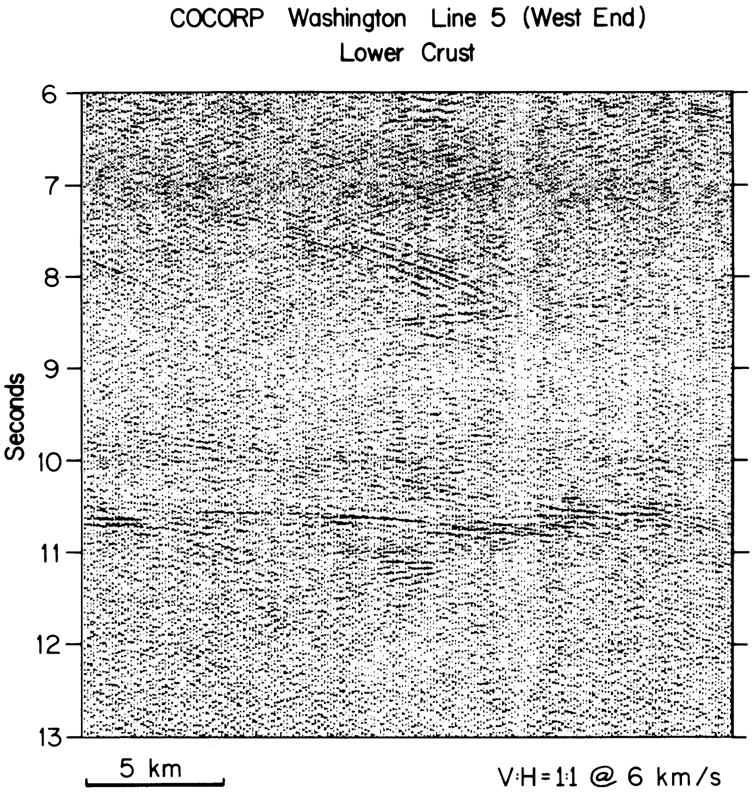

Fig. 5. Detail from an unmigrated seismic section corresponding to part of the section shown in Figure 4 showing the lower crust and Moho beneath the west end of Washington line 5. East dipping reflections and west dipping reflections at 7-9 s uncross on migration, as shown in Figure 2b. The east dipping reflections at 7.0-10.7 s are interpreted as lower crustal ductile deformation zones which formed during Eocene extension; the deepest of these reflections soles into strong Moho reflections at about 10.7 s. The west dipping reflections at 6-9 s, which are cut by the east dipping reflections (after migration, Figure 2b), may be interpreted as ductile deformation fabric that formed in the deep crust during Mesozoic compression, or as pre-Mesozoic deep crustal structure. Refer to text for details.

travel times greater than Moho reflection times on the west end of Washington line 2 (VPs 50-200, Figure 3) has a stacking velocity of 4 km/s and therefore is best interpreted as a near-surface sideswipe effect and not as a reflection from the deep crust or upper mantle.

In the vicinity of the Kootenay arc, reflections are imaged to travel times of about 11.0 s beneath Washington line 3 and 11.7 s beneath Washington line 4. On line 3 the reflections at 11.0 s are continuous. The sections are devoid of reflections at later times, suggesting that a boundary at these travel times, separating reflective from nonreflective material, represents the Moho. If so, the Moho is as much as 3 km deeper beneath the Kootenay arc than beneath adjacent areas.

DISCUSSION

Interpretations of the seismic data discussed above are based primarily on integration of regional reflection patterns with surface geologic patterns and to a lesser degree on projection of reflections to surface features. For example, interpretation of west dipping reflection sequences A-E as a crustal scale thrust system is based on the pattern of these reflections on the COCORP transect and their position with respect to basement uplifts, the Kootenay arc, and

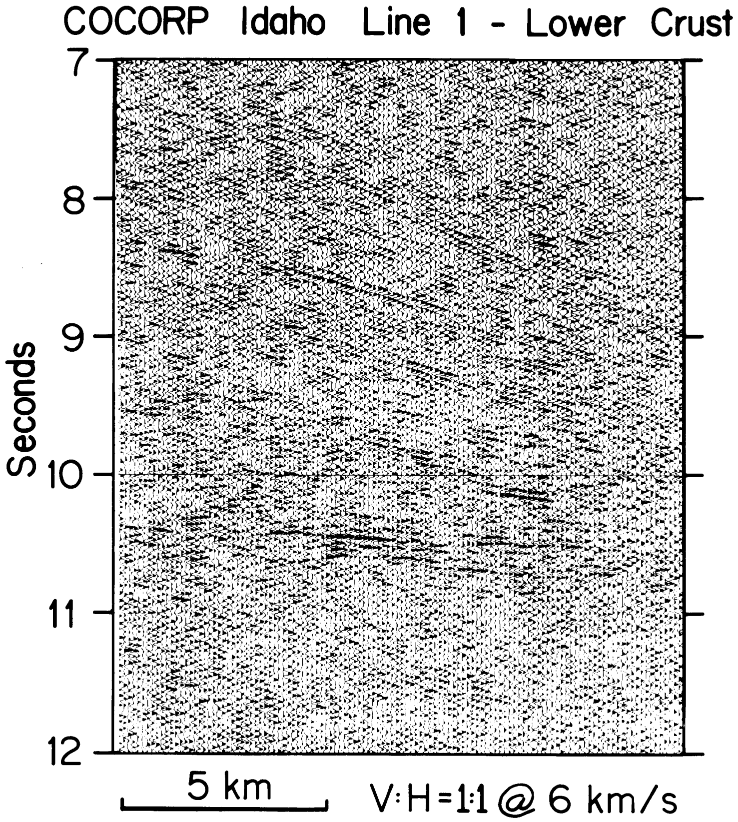

Fig. 6. Lower crust and Moho beneath COCORP Idaho line 1. This is an unmigrated seismic section; vertical scale is two-way travel time. Note strong Moho reflections at 10.4-10.8 s, with gently east dipping reflections directly above them; dips of east dipping reflections steepen at successively shallower levels in the deep crust. The east dipping deep crustal reflections are interpreted as broad ductile deformation zones which developed during Eocene extension. See text for details.

thrust belt structure to the east. This thrust system does not reach the surface along this transect, so correlation with specific structures is impossible.

Moho

Recognition of the Moho as a flat surface which underlies a complexly deformed crust suggests that its geometry was developed late, during or after the latest significant crustal deformation. (Similar conclusions were reached from seismic data along the COCORP 40°N Cordilleran transect by Klemperer et al. [1986], Potter et al. [1986], Hauge et al. [1986], and Hauser et al. [1986]). Thus the observed Moho geometry probably developed in Cenozoic time, during widespread Eocene magmatism and extension, or during Miocene magmatism and extension related to generation of the Columbia River basalts exposed just to the south. This would require that the lower crust, which had been overthickened during thrusting and may have been bounded beneath by an irregular Moho, was significantly mobilized during Cenozoic extension, both by ductile flow and by partial melting, as the crust was drawn out into its new configuration. The result was a flatter Moho beneath thinned crust; development of the flat Moho may have been intimately related to ductile and magmatic flow in the lower crust.

Crustal Extension

Widespread Eocene cooling ages in metamorphic complexes [Fox et al., 1977; Miller and Engels, 1975], prominent Eocene normal faults [Tempelman-Kluit and Parkinson, 1986; Rhodes and Cheney, 1981; Harms, 1982], and thick Eocene volcanic and nonmarine sedimentary sequences [Pearson and Obradovich, 1977; Monger, 1968] all attest to the strong overprint of Eocene extension in the region crossed by the COCORP lines. Deep seismic data should provide clues to crustal scale extension mechanisms and allow us to identify and "look through" the extension-related crustal structure order to gain a clear picture of earlier compression-related structure.

West dipping normal faults (Okanogan Valley fault, [Tempelman-Kluit and Parkinson, 1986] and Bodie Mountain fault [Pearson, 1967] are the dominant extensional features in the western part of the transect (Washington lines 1 and 2). These faults are not well imaged on the COCORP data. A detailed three-dimensional study by Sanford [1986] suggests that the Bodie Mountain fault remains gently dipping beneath the Toroda Creek Graben and may resurface as an east dipping fault along the east flank of the Okanogan Dome. If so, it is possible that the Bodie Mountain fault and the Okanogan Valley fault are part of a single, warped detachment surface, as illustrated in models for core complex evolution by Spencer [1984] and Wernicke [1985].

East dipping reflections G (described above) and the east dipping mylonite zone into which G projects in the Okanogan Dome may also represent an Eocene normal fault older than the west dipping Bodie Mountain and Okanogan Valley normal faults exposed in that area. G can be traced into gently east dipping reflections at 5.0-5.5 s (about 15.0-16.5 km) beneath VPs 50-250 on Washington line 2 (Figures 2 and 3) [Sanford, 1986].

The bounding faults of the Republic Graben, which lies between the Kettle and Okanogan domes, are probably not large-displacement faults, since they are not associated with thick mylonite zones similar to those exposed beneath the Okanogan Valley and Kettle River faults [Orr, 1985b]. The Granby Fault (Figure 1) is not imaged on the COCORP data. Gently east dipping reflections at 2-3 s between VPs 540 and 650 on Washington line 2 (Figure 2) project toward the surface location of the Bacon Creek fault (Figure 1) and are interpreted as the Bacon Creek fault. These reflections intersect west dipping reflections interpreted as thrust structure beneath the east end of line 2 at about 3 s.

Beneath the area crossed by Washington lines 3-5 and Idaho line 1, and adjacent parts of British Columbia, major normal faults mapped at the surface are east dipping, with the exception of the spoon-shaped Newport fault. The major east dipping faults include the Kettle River fault (Figure 1) [Rhodes and Cheney, 1981; Hurich et al., 1985], the Slocan Lake fault [Parrish et al., 1985] which forms the eastern boundary of the Valhalla Complex, and a normal fault occupying the Purcell Trench [Rehrig et al., 1982]. All of these fault zones are characterized by brittle faults superimposed on thick mylonite zones, similar to the boundaries of other core complexes [Crittenden et al., 1980; Armstrong, 1982].

The Kettle River fault can be traced from its surface exposure, along a gently (12°) east dipping reflection beneath the east end of Washington line 3. This reflection projects towards prominent, gently east dipping reflections J, to a depth of 12-15 km beneath the east end of Washington line 4, defining a surface which may have been a major Eocene extensional detachment.

The Newport fault (Figure 1) has a U-shaped map trace and is also marked by a chloritic breccia zone above a mylonite zone. Harms [1982] interprets this structure as the product of large-scale crustal necking during Eocene extension. As described above, the west branch of the Newport fault may be traceable from its surface exposure to a depth of about 9 km beneath the east end of Washington line 5 (Figure 2).

In summary, some Eocene normal faults can be traced to midcrustal depths on the COCORP data, but none can be clearly traced directly into the deep crust. Possible deep crustal continuations of normal faults occur beneath Washington line 2 and Idaho line 1. The east dipping reflections at 6-8 s (migrated depth 17-23 km) beneath the east end of Washington line 2 (Figure 2) may be the deep continuation of zone G and related reflections. East dipping reflections at 7.0-10.2 s (migrated depth 20-29 km) beneath Idaho line 1 (Figures 2 and 6) project toward midcrustal east dipping reflections beneath the east end of Washington line 5, which project toward the west "branch" of the Newport fault. These east dipping, deep crustal reflections can be related to exposed normal faults only by extrapolating across data gaps or areas of poor data quality (few reflections), 10-20 km in width. Thus they can only tentatively be tied to surface structure.

The interpretation of the deep, east dipping reflections as Eocene extensional features is dependent on the observation that they appear to cut across a thrust-related west dipping set of reflections, as suggested by the migrated line drawings of Washington line 5 and Idaho line 1 (Figure 2b). It is unlikely that these east dipping structures would be Cenozoic thrusts antithetic to thrust belt structures, since no such structures are documented at the surface; the only significant post-Paleocene west verging structures to the west are related to Eocene and younger subduction off the Washington coast. East dipping middle to lower crustal reflections could be related to west verging Jurassic(?) thrusts such as those mapped by Yates [1971] along the Columbia River near Northport, Washington, which carry North American sedimentary rocks over accreted rocks of the Intermontane Terrane. Brown et al. [1986] suggested that such west verging thrusts cut into the deep crust but were later cut off along east verging thrusts. Since this crosscutting relationship is not apparent on the seismic sections, and in fact, the data suggest that the east dipping structures cut the west dipping structures, the interpretation that we favor is an east dipping deformational fabric associated with Eocene extension, cutting older west dipping thrusts.

The presence of both east and west dipping reflections throughout the crust in parts of this reflection transect suggests the possibility that the crust has extended along anastomosing shear zones which form a series of crustal lenses, as suggested by Hamilton (1982). Our interpretation emphasizes the possibility that the prominent west dipping reflections are relicts of an earlier crustal scale thrust system, but the anastomosing lens extensional model cannot be unequivocally ruled out.

The regionally developed pattern of deep crustal east dipping reflections beneath the eastern part of the transect may represent broad ductile deformation zones which accommodated normal sense displacement in the lower crust; these reflections may locally merge with the Moho (beneath Washington line 5 and Idaho line 1), suggesting that the deformation zones sole into the Moho. The east dipping features may include localized zones, continuous with discrete upper crustal detachments (as suggested by Wernicke [1985]). Alternatively, the east dipping reflections may be the signature of distributed lower crustal extension; normal faults which can be traced to the middle crust may not continue deeper as discrete features, being accommodated instead by distributed ductile flow, still with dominantly east dipping structure which soles into the Moho. Beneath the Newport fault, where extreme necking and boudinage of the upper and middle crust in the Eocene have been proposed by Harms [1982] and Harms and Price [1983], deeper, east dipping deformation zones may have accommodated extension in the middle and deep crust. The COCORP data suggest that the necking and boudinage model inferred from the surface geology [Harms, 1982; Harms and Price, 1983] does not apply to the entire crust. At the base of the crust, extensional structures soled into a remarkably flat Moho, as imaged on the reflection data, in contrast to the considerable relief on Eocene detachments exposed at the surface. The data also suggest that lithosphere-penetrating simple shear, as envisioned by Wernicke [1985], does not apply in this region but that the Moho served as a fundamental detachment surface during Eocene extension.

Thrust Structure

In the interpretation shown in Figure 2c, thrust faults are preserved in panels bounded by Eocene normal faults. Restoration of displacement along the Eocene normal faults would result in a configuration consisting of stacked thrust faults beneath the Okanogan and Kettle domes, similar to the crustal duplex geometry shown beneath the Shuswap Complex by Monger et al. [1985] and Brown et al. [1986]. Such a restoration is not attempted here because of uncertainties in correlating specific thrust structures and because the 55 km NE-SW offset between Washington lines 4 and 5 makes it difficult to relate structures interpreted beneath Washington line 5 and Idaho line 1 to those beneath Washington lines 1-4.

Monger [1984] suggests that the 2.0 Ga basement exposed in the Shuswap Complex in British Columbia may be an allochthonous piece of continental crust, since North American basement to the east gives 1.7 Ga radiometric dates. If so, reflections A and B may represent a suture between this allochthonous continental sliver (which would include gneisses of the Okanogan and Kettle domes) and North America. In the middle and deep crust beneath Washington line 1, subhorizontal reflections at 5.5-6.0 s between VPs 1 and 350 are interpreted to represent structures (possibly a higher thrust) deformed above, and truncated by, the inferred thrust zone represented by reflections A (Figure 2).

The shallowest thrust beneath the crystalline Priest River Complex on Washington line 5 is interpreted just above or along the top of reflection sequence D. Deeper, west dipping reflections beneath D may represent thrust-imbricated metasediments or mylonitic thrust zones. Either of these interpretations suggests that thrusts beneath Washington line 5 penetrate to 21-km depth (Figure 2).

Beneath Idaho line 1, west dipping and subhorizontal reflections from 1.5 to 5.4 s (including E) are interpreted as thrust structure. A few short horizontal reflections occur between 5.5 and 7 s, and a very strong overprint of east dipping reflections dominates the seismic section below 7 s, so it is not clear that thrusts occur below 5.5 s. The west dipping structures on Idaho line 1 are probably correlative with part of the west dipping sequence at 1.5-7.0 s beneath Washington line 5, but it is impossible to correlate specific reflections because of the overprint by east dipping reflections on Idaho line 1, and uncertainty about the amount of normal sense offset along an inferred east dipping normal fault zone (Figure 2c) which intervenes between the two west dipping zones.

The very reflective sequence directly beneath D (and probably E) may represent metasedimentary rocks and metamorphosed sills of the Proterozoic Belt Supergroup over which basement rocks of the Priest River Complex were thrust. Proterozoic sills imaged on seismic lines beneath the Purcell Anticlinorium form reflective zones of approximately the same thickness as D [Harrison et al., 1985]. Alternatively, these reflections along with deeper, more westerly thrust-related reflective sequences (A and B) may be from broad ductile deformation zones similar to the mylonitic zones exposed at the surface in the metamorphic complexes along the COCORP transect and in more extensive exposures of the Shuswap Complex to the north [Rhodes and Hyndman, 1984; Parrish et al., 1985; Journeay and Brown, 1986].

Reactivation of Structures

Two high-amplitude gently dipping upper crustal reflection sequences (D and J) underlie steeply dipping, complexly deformed surface structure on Washington lines 4 and 5; for this reason, detachment surfaces are interpreted directly above or within these reflective zones. These reflections may originate from broad (mylonitic?) fault zones which accommodated both normal and thrust displacements. As noted above, J (Figure 2) can be interpreted as a Mesozoic backthrust or as an Eocene detachment. If it is a Jurassic backthrust, it may have formed the upper surface of an eastward driven wedge of accreted rocks which delaminated the upper part of the crust [Price, 1984, 1986]. Alternatively, it was an early west directed thrust which rooted to the east in the deep crust, similar to structures in a model advanced by Brown et al. [1986]. In either case its position with respect to the Kettle River fault suggests that it was reactivated during Eocene extension. The thrust interpreted at the top of D (Figure 2), which carried Proterozoic basement, complexly deformed Proterozoic and Paleozoic strata, and Mesozoic plutons in its upper plate, may also have been reactivated during the Eocene, accommodating some of the displacement related to the spoon-shaped Newport normal fault (Figures 1 and 2).

Intrusions

The COCORP lines cross several large granitic plutons, mainly of Cretaceous age (Figure 1). Beneath Washington lines 4 and 5 the plutons are underlain by an unreflective uppermost crust and gently dipping, prominent reflection sequences D and J (Figure 2), the upper bounds of which occur at travel times of 2-3 s. D and J are much more extensive than the surface exposures of the plutons. While it is possible that these prominent dipping reflections are related to intrusive structure, it is more likely that they represent faults, as discussed above, and that the plutons were displaced above late Cretaceous to Paleocene thrust faults as well as Eocene normal faults. Detailed

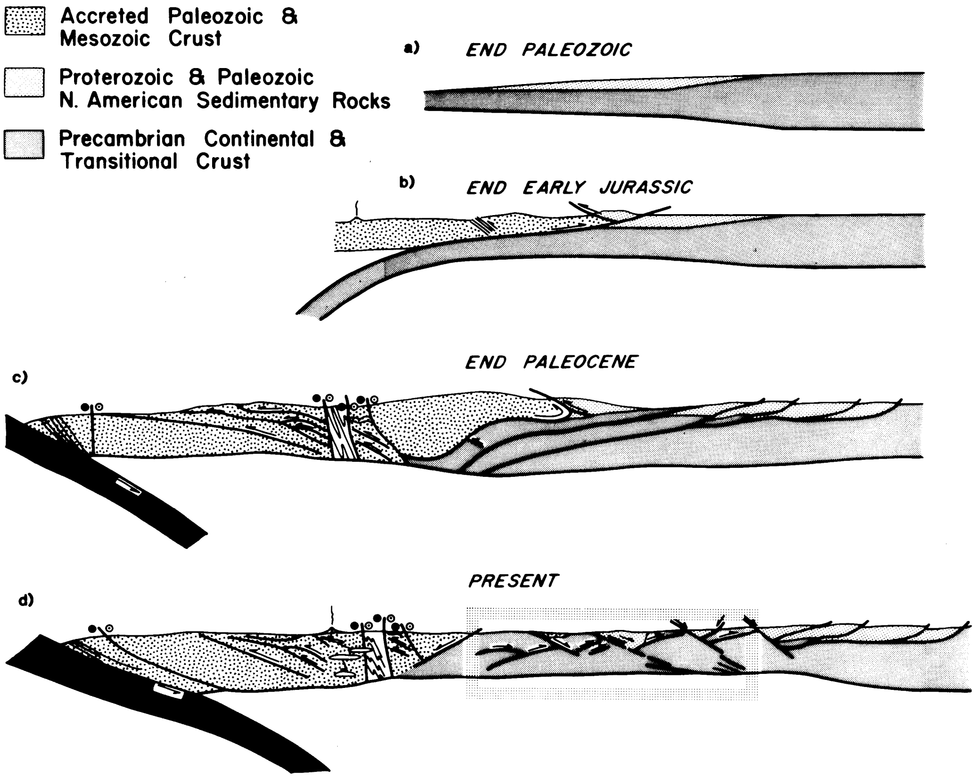

Fig. 7. Evolutionary diagram for Cordilleran interior and thrust belt at ~49°N, showing schematic development of major crustal features. (a) Passive margin configuration, which was initiated during Proterozoic rifting and existed into early Mesozoic time. (b) Early Jurassic thrust emplacement of the Intermontane Terrane [Price et al., 1985], a previously amalgamated arc/oceanic collage, above the passive margin. (c) Crustal configuration at the end of Paleocene time, following the mainly transpressional accretion of terranes in the western Cordillera, thrust imbrication of basement slices in the interior of the Cordillera, and development of the Rocky Mountain fold and thrust belt in the eastern Cordillera. (d) Present-day crustal structure, showing results of Eocene extension in the interior, further dextral offset on major transcurrent faults, and development of the Cascade arc above the subducting Juan de Fuca plate. The stippled box corresponds to the area crossed by COCORP lines discussed in this paper; a detailed interpretation of crustal structure in this area is shown in Figure 2c.

radiometric dating and geologic synthesis in this region suggests that Cretaceous plutons were displaced during thrusting [Archibald et al., 1983, 1984]. Weak, moderately dipping reflections which lie above both D (line 5, VPs 400-440) and J (line 4, VPs 175-300) at 1.5-2.5 s may be related to structure within or at the base of these plutons. A Tertiary pluton exposed at the eastern end of line 2 within the Kettle Dome is also underlain by west dipping reflections at 1-2 s.

Cordilleran Evolution

An evolutionary model for development of the Cordilleran interior at this latitude, incorporating the results of this COCORP survey, is shown in Figure 7. The model includes Mesozoic structural thickening of Proterozoic transitional crust in the Cordilleran interior, following Jurassic thrust emplacement of the easternmost accreted terranes, in a fashion similar to that proposed by Monger et al. [1985] and

Brown et al. [1986]. According to this model, west dipping reflections on Washington lines 1-4 are part of a basement duplex which imbricated transitional crust west of the rifted edge of the North American craton. Shallower, basement-involving thrusts east of the Kootenay arc, on Washington line 5 and Idaho line 1, apparently transported thinner lenses of basement (one of these would be the Priest River Complex), and allochthonous basement slices may underlie the thrust belt as far east as the Purcell Anticlinorium [Harrison et al., 1980, 1985; Cook, 1985].

Figure 7d shows a schematic view of the present crustal structure of the Cordillera including the geometry of Eocene extensional structures inferred from the COCORP data in the interior. According to this model, Eocene shear zones continued as discrete zones into the middle crust, where they passed into broader dipping deformation zones that soled into the Moho, which acted as a decoupling surface during extension. In this way the Moho developed a subhorizontal, smooth geometry during crustal extension. Development of this smooth Moho geometry may have also been influenced by synextensional magmatism ("Challis arc," Eocene volcanism of Idaho, NE Washington, and southern British Columbia), at least some of which was mantle derived. Mantle-derived magmas would heat and soften the lower crust, facilitating lower crustal deformation and allowing large ductile strains to develop over a relatively short time span during Eocene extension.

The model for postthrusting crustal extension proposed above for this part of the Cordillera may be applicable, in a general sense, to other parts of the Cordillera and to other mountain belts. Caution should be taken, however, in application of this specific model to these other regions. For example, while postthrusting crustal extension of the interior was apparently very important to the south in the U. S. part of the Cordillera, the timing of the crustal extension there was later than that in the northwest United States [Armstrong, 1982]. Eocene extensional structures can be traced to the north, into the central part of the Shuswap Complex of southern British Columbia [Parrish et al., 1985; Tempelman-Kluit and Parkinson, 1986; Journeay and Brown, 1986], but the magnitude of Eocene extension may have been much less north of about 51°N latitude [Brown and Read, 1983; Okulitch, 1984]. The northern part of the late Mesozoic and early Tertiary Shuswap Complex may be more directly analogous to the present-day Himalayas, where normal faults accommodate extension in the upper and middle parts of the overthickened crust, as continental shortening continues at depth [Burchfiel and Royden, 1985]. If true, this suggests abrupt along-strike variation in the amount of early Tertiary postthrusting extension in this part of the Cordillera.

CONCLUSIONS

The COCORP transect across the Cordilleran interior in Washington and Idaho suggests the existence of a deeply penetrating thrust system that linked shortening in the accreted terranes and subduction complexes (to the west) with the foreland thrust belt (to the east).

Shortening within the interior probably occurred in a crustal duplex, as suggested for the Shuswap Complex by Monger et al. [1985] and Brown et al. [1986]. The recognition of extensive, broad zones of displacement, some of which accommodated Mesozoic shortening, others Eocene extension, and still others both, is another feature common to both the COCORP data and geology exposed in the southern part of the Shuswap Complex [Parrish et al., 1985; Price et al., 1985; Journeay and Brown, 1986]. Models proposed above suggest that the COCORP profiles image crustal scale, normal sense simple shear zones which accommodated Eocene extension and that these zones soled into the Moho in a thermally softened lower crust. Taken in total, these data provide a provocative example of structures which record the "life cycle" of the Cordilleran interior, from its accretion- and thrust- related constructional phase, through the development of an overthickened crustal welt, to its extensional demise as the welt collapsed after shortening ceased. These data may serve as a crustal scale example of similar cycles documented geologically in individual Cordilleran core complexes [Armstrong, 1982; Coney and Harms, 1984] and as a working model to be compared with crustal evolution in other major compressional orogens, such as the Caledonides, Alps, and Himalayas.

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