INVESTIGATION OF THE MIDDLE-TO-UPPER CRUSTAL STRUCTURAL FRAMEWORK FOR THE WABASH VALLEY SEISMIC ZONE FROM HIGH-QUALITY SEISMIC REFLECTION PROFILES

Final Report

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Abstract. Reprocessing of seismic reflection data reveals new images of upper- to middle-crustal structures beneath the Wabash Valley seismic zone, which is located north of the New Madrid seismic zone within the seismically active southern Illinois basin. Four newly available intersecting deep seismic profiles (243 km, total) indicate an anomalous zone of moderately dipping and diffractive high-amplitude reflectivity beneath the western flank of the Wabash Valley fault system (WVFS), a major zone of northeast-trending normal and strike-slip deformation along the border area of Illinois, Kentucky, and Indiana. The anomalous dipping reflector zone contrasts with the nondescript horizontal crustal reflectivity that is characteristic of the Illinois basin to the north and west. The upper crust beneath the WVFS is dominated by west-dipping planar reflectors that correspond in places to very gently arched regions of overlying Paleozoic strata. The dominating dip in the middle crust beneath the WVFS switches from northwest to southeast, along strike from south to north. The 3-D orientation and structural style of reflectors also varies consistently between the upper and middle crust beneath the WVFS suggesting an intervening level of detachment. Two interpretations are admissible for the observed crustal reflectivity: (1) stratified remnants of a deeply buried Precambrian sedimentary basin like observed elsewhere in the central USA Midcontinent, locally deformed, and with a possible igneous component; (2) compressional deformation (e.g., blind thrust faults) associated with an undetermined Pre-Appalachian-Ouachita tectonic event, possibly the distal Grenville orogeny. The complex dipping crustal reflectivity beneath the WVFS is typical of Paleozoic continental convergent zones observed elsewhere (e.g., Appalachian orogen) and thus may suggest a preserved Proterozoic suture. The area encompassing the reflection profiles has experienced several moderate magnitude ($3.0 \leq m_{bLg} \leq 5.5$) earthquakes during the past 50 years, defining the central part of the Wabash Valley seismic zone. The hypocenter of the largest 20th century earthquake in the central Midcontinent (1968.11.09 m_{bLg}=5.5) is located near the zone of dipping middle crustal reflections just west of the WVFS where the reflector structure is locally most prominent. Both the focal mechanism (moderately dipping reverse fault) and the expected rupture parameter (~2.9-km fault length) of the earthquake are consistent with the orientation and size of observed reflectors. Our observation that middle crustal reflectors dip at a shallower angles than those of earthquake nodal planes may mean that deep earthquakes of the Wabash Valley seismic zone are nucleating along subsidiary structures, too steep to be imaged directly, but closely related to the observed reflector fabric. The results of our study suggest that the seismogenic source just north of the New Madrid seismic zone may consist, in part, of a pre-existing fabric of blind thrusts and/or deeply buried basinal structures that could be reactivated by contemporary stress.

Non-technical Summary

Industry seismic reflection profiles over the Wabash Valley Seismic Zone in Illinois and Kentucky were reprocessed in order to extend the record from 5 s to 8 s travel time (or approximately 25 km depth). The resulting images show the structure of the earth's crust to be dominated by dipping reflecting surfaces that represent strong deformation. One of these surfaces corresponds to the earthquake focus (point of initial rupture) for the 1968 southern Illinois earthquake, which was the largest event in the central USA Midcontinent during the 20th century. Even though such deep dipping reflectors are fairly common beneath parts of the Appalachian Mountains and other orogenic belts, where they are interpreted as compressional features, they are unexpected beneath the so-called stable continental interior. The reflector-focus correlation supports the reactivation of pre-existing geologic structure by the modern stress field.

1. Introduction

Despite many studies documenting the distribution and source parameters of the larger earthquakes in "stable continental regions" (see *Johnston and Kanter* [1990] for review), little direct subsurface information on the geologic and tectonic setting of intraplate seismicity is available [*Crone et al.*, 1997]. The New Madrid seismic zone (NMSZ) (Fig. 1), located in the central Mississippi River valley, is one of the most intensively studied seismic zones in the world [*Johnston and Schweig*, 1996]. The epicenter, hypocenter, and focal mechanism patterns of the NMSZ are well defined [*Chiu et al.*, 1992] and mark a relatively discrete line of strike slip interrupted by a transverse zone of southwest-dipping thrust faulting (Fig. 1). A more dispersed zone of seismicity continues farther north into southern Illinois known as the Wabash Valley seismic zone (WVSZ) [*Nuttli and Herrmann*, 1978; *Nuttli*, 1979] (Fig. 1). Although seismicity patterns are poorly constrained in this region, the southeastern Illinois area over the past half-century has hosted several instrumentally recorded events of magnitude (m_{bLg}) 3.0 or greater, of which the 1968 event is the largest and one of the deepest (Fig. 2) (Table 1). According to the comparative study of *Gordon* [1988], earthquakes here are deeper than elsewhere in the central United States. In the southern Illinois basin earthquake focal mechanisms are a combination of interpreted NNE-trending dextral strike-slip and reverse faulting (Fig. 1) [*Taylor et al.*, 1989] and reflect the characteristic deformation modes for earthquakes in this region [*Langer and Bollinger*, 1991]. In agreement with seismicity-derived deformation, other contemporary stress indicators for the region show a shift from an E-W maximum horizontal compressive stress axis at the latitude of the NMSZ to one that is just north of east in southern Illinois and Indiana [*Zoback and Zoback*, 1981; *Nelson and Bauer*, 1987; *Hamburger and Rupp*, 1988; *Ellis*, 1994] (Fig. 1).

In recent years, the WVSZ has become more intensely studied using GPS-based geodesy [*Rupp et al.*, 1999], high-resolution seismic monitoring [*Pavlis et al.*, 1999], shallow seismic reflection and georadar investigations [*Bodziak et al.*, 1999], reinterpretations of conventional petroleum exploration seismic data [*Bear*, 1997; *Bear et al.*, 1997], and earthquake-induced paleoliquefaction mapping [e.g., *Obermeier*, 1998]. Except for the single COCORP (Consortium for Continental Reflection Profiling) profile that extends across the northern end of the zone [*Pratt et al.*, 1989], the use of deep seismic reflection has not been applied. Consequently, little is known of the Precambrian upper or middle crustal structure beneath the WVSZ. The Wabash Valley fault system (WVFS), a major zone of northeast-trending normal and strike-slip faulting along the border area of Illinois, Kentucky, and Indiana [*Bristol and Treworgy*, 1979; *Nelson*, 1995] within the center of the WVSZ (Fig. 2) has long been suspected to be related to the source of the seismicity [*Stauder and Nuttli*, 1970; *Mitchell et al.*, 1991]. However, earthquakes here do not correlate with any known structures as mapped from numerous drill holes within the Paleozoic Illinois basin (Fig. 2). Thus, investigating the deep structure of the WVFS could be an important step toward understanding Precambrian basement in this part of the USA Midcontinent and providing some constraints on the seismogenic source north of the NMSZ.

In order to study upper and middle crustal structure beneath the WVFS, we present the results of four intersecting deep seismic reflection profiles reprocessed for this study to at least 8 seconds (s), totaling 243 km in length that have not previously been published. The lines constitute a nearly closed parallelogram loop over the western flank of the WVFS with two profiles oriented in a "dip" sense and two in "strike" sense with respect to the fault system (Fig. 2). The profiles cover the area where the largest instrumentally recorded seismic activity has been reported within the WVSZ. One of the profiles passes within 5 km of the epicenter of the 1968.11.9 m_{bLg}=5.5 earthquake [*Stauder and Nuttli*, 1970; *Gordon*, 1988; *Langer and Bollinger*, 1991]. The 1968 event is significant for intraplate seismicity in a worldwide context because it was the largest 20th-century earthquake for the central North American Midcontinent, and is typical of intraplate seismic deformation in the sense of being "deep" (>15 km), compressional, and in an area of low heat flow within the center of a stable continental region [*Chen*, 1988].

2. Geologic Setting

The roughly oval shaped Illinois basin contains as much as 7 km thickness of Cambrian through Pennsylvanian sedimentary rocks [*Buschbach and Kolata*, 1991]. The age and lithology of the Precambrian basement are poorly known beneath the Illinois basin, but scattered industry drill holes have penetrated felsic igneous rocks [*Hoppe et al.*, 1983; *Buschbach and Kolata*, 1991; *Sargent*, 1993] thought to be part of the 1.45-1.51 Ga "eastern granite-rhyolite province" [*Bickford et al.*, 1986]. The New Madrid "rift complex", which includes the Reelfoot rift and the Rough Creek graben and which is at least as old as Early Cambrian, underlies the southern part of the Illinois basin, south of the Rough Creek-Shawneetown fault zone [*Kolata and Nelson*, 1991] (Fig. 2). The southern part of the Illinois basin, near the NMSZ, is the most structurally complex region in the basin and has a long history of faulting and reactivation [*Heigold and Kolata*, 1993; *Potter et al.*, 1995; *Kolata and Nelson*, 1997; *McBride*, 1998]. The dominating structure in this region is the northeast-striking WVFS (Fig. 2). The faults outline elongated gently tilted or arched horsts and grabens, with the axial portion down-faulted relative to the margins [*Nelson*, 1995]. Drill hole data indicate predominantly normal movement along the faults that is post-late Pennsylvanian in age [*Nelson and Lumm*, 1987; *Nelson*, 1995]. Recent analysis of industry reflection data across the fault system [*Bear et al.*, 1997] indicates Cambrian fault movements including early Paleozoic dextral strike slip along some of the faults. *Sexton et al.* [1986] argued that the faults of the WVFS developed by reactivation of a Precambrian rift zone that was a northern extension of the New Madrid rift complex based on the interpreted continuity of gravity and magnetic anomaly patterns [*Braile et al.*, 1982]. *Bear et al.* [1997], however, concluded that the fault system is not a northward continuation of the Reelfoot rift portion of the New Madrid rift complex because fault displacements of the WVFS decrease to the south.

3. Seismic Reflection Data

One vibroseis and three dynamite-source industry seismic reflection profiles were surveyed in 1985 and in 1988-1989, respectively, over the WVFS and vicinity. The data owners processed only the upper 5 s of the 8-s dynamite records and 4 s of the correlated vibroseis records. The longest (77 km) and key profile (A) begins in western Kentucky just north of the Rough Creek-Shawneetown fault zone, crosses the WVFS, and extends northwestward deeper into the Illinois basin (Fig. 3). A parallel dip profile (B) 40 km to the north begins at the Wabash River and extends 59 km to the northwest (Fig. 3). The WVFS can be divided into two zones, south and north, based on the strike and continuity of the westernmost faults (Fig. 2). Profile A crosses the WVFS in an area where the faults are less continuous than to the north and where they strike almost due north. Just north of profile A, the strike of the faults abruptly switches to northeast and the faults become more continuous. Profile B crosses the north zone (Fig. 2). One strike profile (C, 56 km) connects lines A and B near their northwestern ends, while another (D, 51 km) cuts through line B towards its southeastern end (Fig. 3). The acquisition and original contractor processing parameters of the dynamite surveys (A, B, C) have been discussed previously by *McBride et al.* [1997] and *Potter et al.* [1997] and the acquisition and original contractor processing parameters of the vibroseis survey (D) by *McBride and Kolata* [1999].

The original dynamite shot-record data were reprocessed to include the full recorded 8 s and to enhance images of deep crustal structure. The uncorrelated vibroseis records were reprocessed so as to extend the correlated record length from 4 s to 16 s using the self-truncating extended cross-correlation method [*Okaya and Jarchow*, 1989] in which frequency bandwidth decreases with traveltime for the extra correlation time. Because the present study is focused primarily on crustal structure at or below 15 km depth, the data processing parameters were oriented toward enhancing lower frequency signal. The most important departures from the original processing strategy were: (1) a 10-120 Hz frequency passband filter (Ormsby), (2) subsample to 8 ms, and (3) test migrations over a range of constant velocities (3.0 to 6.5 km s^{-1}). Finite-difference, frequency-wavenumber, and phase-shift migrations (see *Yilmaz* [1987] for review) were tested on the stacked data using various constant migration velocities. The optimum migration results were obtained with the phase-shift method (10-80 Hz). A simplified or constant velocity structure is appropriate because we aimed the reprocessing at the post-2-s record and because information on local crustal velocity variations is unavailable. Several migration trials were performed to avoid overmigration artifacts and to determine which apparently linear events might be diffractions. The resulting new images maximize the expression of deep crustal reflectors. Time-to-depth conversions were carried out using information from nearby drill hole data and extrapolated from seismic refraction-based models of the crust for the northern Mississippi Embayment [*Ginzburg et al.*, 1983; *Catchings*, 1999]. Reflector dips are apparent unless otherwise noted. For this study, we define the terms "upper" and "middle" crust to refer to depth ranges of 0-12 km (roughly 0-4 s) and 12-24 km (roughly 4-8 s), respectively, based on a 36-km thick crust [*Allenby and Schnetzler*, 1983].

4. Observations

4.1. "Dip" Profiles (A and B)

Profile A is considered to be the key line since it is a long dip profile (with respect to the WVFS) (Fig. 3), shows the most pronounced middle crustal reflectivity, and is closest to the 1968 epicenter. Profile A is presented as an interpretive line drawing (Fig. 4a), on which we omitted suspicious events (e.g., residual diffractions and remaining multiple reflections). The upper ~1.8 s of the record, discussed in detail by *Bear et al.* [1997] and *Potter et al.* [1997], is a layered sequence of nearly horizontal reflections that correspond to the well-known Paleozoic strata of the Illinois basin. The WVFS is expressed only as subtle offsets within the Paleozoic section (Fig. 4a). The upper part of the basement (~1.8-4.0 s) consists of a broad prominent reflective sequence, in which reflectors are subhorizontal or inclined with a strong west-dipping component. Beneath the central part of the Illinois basin the reflective sequence steepens and plunges deeper into the crust just west of the Albion-Ridgway fault zone (Fig. 2) over the 1968 hypocenter (Fig. 4a, km 32-37). At deeper levels (e.g., beneath km 33, between 6.5 and 8.0 s, Fig. 4a), both west and east dipping reflections are present, although west dips dominate. Widely separated drill holes [*Buschbach and Kolata*, 1991; *Potter et al.*, 1997] suggest that the upper basement reflectivity may be the expression of possible sediments and/or layered igneous rocks of the eastern granite-rhyolite province referred to above [cf. *Pratt et al.*, 1989]. Due to the limited number of basement penetrations, it is questionable how well a granitic lithology represents basement reflectivity beneath this part of the Illinois basin (see also *Pratt et al.* [1992] and *McBride and Kolata* [1999]).

The deep west-dipping reflections are expressed as a broad series composed of three widely spaced, imbricate sets extending to the bottom of the 8-s record (as marked by three arrows in Fig. 4a). The most prominent of the deep west-dipping reflections begins at 7.1 s on profile A (center part), dips 21° using an upper-to-middle crustal velocity of 6.2 km s^{-1} [*Ginzburg et al.*, 1983], and continues to the bottom of the 8-s stacked section. Applying migrations with interval velocities up to 6.0 km s^{-1} (Fig. 4b) indicates the proper behavior of in-plane reflections that appear as a strong, planar events on the unmigrated section (Fig. 4b). The middle crustal reflections on the center part of profile A are situated beneath a pronounced bend and offset in the base of the upper basement sequence (km 15-22, Fig. 4a). The offset within the basement spatially matches the position and sense of offset of the westernmost fault of the WVFS (Albion-

Ridgway fault), which is a predominantly normal fault down-thrown to the east, even though the Albion-Ridgway fault appears not to substantially displace lower Paleozoic reflectors. On the other hand, the three sets of deep dipping reflections themselves have no collinear relation to the faults of the WVFS.

Unlike profile A, profile B crosses the WVFS where the westernmost faults strike in a northeast direction (Figs. 2 and 3). The highly reflective Paleozoic section delineates an arch corresponding to the WVFS that is bounded on either side by faults that affect the entire Paleozoic section. The westernmost fault (part of the Albion-Ridgway fault zone) can be traced through the Paleozoic strata into the Precambrian basement to a traveltime of 3.0 s on the basis of offset reflectors (Fig. 5) and by following the loss of reflection coherency directly along the fault surface. Like on profile A, an upper basement reflection sequence can be recognized down to about 3.3 s. The shallowest part of this sequence (~1.8-2.2 s, Fig. 3) corresponds to the "Centralia sequence", whose regional extent is limited on the south, between profiles A and B, as shown in Figure 2 [*McBride and Kolata*, 1999]. *Pratt et al.* [1992] defined the "Centralia sequence" to be the "layered Precambrian rocks imaged on the upper 5 s of COCORP lines in southern Illinois and Indiana" just north of the study area. They suggested that it could represent either an unrecognized Proterozoic sedimentary basin or the granite-rhyolite province with perhaps a mafic igneous sill or flow component. Beneath the Centralia sequence, west-dipping (18°) planar reflections appear below and northwest of the Albion-Ridgway fault zone and continue deeper to 4-5 s (Fig. 5). These dipping reflections are approximately on trend with the west-dipping upper crustal reflections on profile A (Fig. 4a), relative to the Albion-Ridgway fault zone. An interesting characteristic of profile B is that reflector geometries differ vertically across a traveltime of 4-5 s (~13 km), which approximately marksa boundary between upper and middle crust. Beneath the western flank of the WVFS beginning at 4.5 s, the reflector geometry abruptly changes vertically from west-dipping planar to east-dipping planar and convex-upward reflections continuing to the bottom of the 8-s record (Figs. 3 and 3). The east-dipping package extends to the east beneath the WVFS from km 24 to km 47 (maximum dip 29°), where it switches back to (or merges with) a west-dipping package similar to that in the uppermost Precambrian crust.

On both dip profiles A and B below or west of the WVFS, the west-dipping reflectors in the upper Precambrian crust occur beneath, and dip up toward, a subtle long-wavelength fold expressed concordantly throughout the Paleozoic section and the upper part of the reflective basement sequence (e.g., Centralia sequence) (Figs. 4a and 3). This pattern is difficult to is clear on highly exaggerated sections (Fig. 6). For profile B, the wavelength of this fold is at least 22 km and the maximum magnitude is 230 m (for 6.0 km s^{-1}). The west-dipping reflectors consistently are positioned with respect to the fold on both dip profiles. On profile A, the dipping reflectors and overlying a more subtle expression of the fold are located somewhat further west of the Albion-Ridgway fault zone than on profile B (Fig. 4a).

4.2. "Strike" Profiles (C and D)

Profile C (Fig. 3), which connects profiles A and B (Figs. 2 and 3), is located outside of the WVFS proper and extends into the deepest portion of the Illinois basin outside the Rough Creek graben [*Buschbach and Kolata*, 1991]. This profile is approximately oriented in a strike sense with respect to the dipping reflections on profiles A and B and with respect to the trend of the WVFS. Within the upper crust, north-dipping reflections immediately underlie the Centralia sequence down to about 4.0 s (Figs. 3). In the middle crust, beginning at 5.5 s, a complex isolated zone of south-dipping reflections (km 20-35) with variable dips of 22-34° extends to the bottom of the record and ties to poorly coherent southeast-dipping reflections on profile B (Fig. 3). Near the southern end of profile C (km 40-55), south-dipping (20°) reflections appear in the upper crust down to 4.5 s (Fig. 3). Below about 5.5 s, again the reflection fabric abruptly switches, in this case to north-dipping (21°) (km 45-57). At the south end of profile C, both north- and south-dipping sets tie to similarly dipping reflections at the northwest end of profile A (Fig. 4a),where the dips of the correlating reflections are both 24° indicating more of a northwest and southeast true dip, respectively (Fig. 3).

Profile D (Fig. 7a) begins within the south-central part of the WVFS (Fig. 2) and continues north into a somewhat shallower portion of the Illinois basin, making an oblique angle with the trends of the faults. Deep beneath the base of the Paleozoic section and Centralia sequence three clusters (x, y, z) of diffractions appear beginning at 4.8 s and continuing to ~9.2 s (Fig. 7a). Upon migration these collapse into discrete zones of horizontal or gently dipping reflection segments (Fig. 7b). This reflectivity appears to be grouped into two tiers centered on 6-7 s and 9 s separated by a reflection-poor zone. In general, the relatively horizontal reflectivity on profile D is the strike-line expression of the dipping reflections on profile B (Fig. 3). The middle of the diffraction clusters, x and y, correlates to the down-dip portion of the middle crustal dipping reflections on profile B (Fig. 3). The presence of strong and numerous diffractions here implies a structural "roughness" with respect to the signal wavelength at this level of the crust associated with the dipping reflections.

5. Geologic Interpretations

Our study, which focuses mainly on the Precambrian crust, is complemented by previous studies of the WVFS within the Paleozoic and shallow Precambrian section, based on shallow (3-4 s) industry reflection profiles [*René et al.*, 1995; *Bear et al.*, 1997; *McBride et al.*, 1997]. *Bear et al.* [1997] have shown that the WVFS has a long and complex history of reactivation. Our deep seismic reflection data shed some light on the crustal structure beneath the WVFS, which has been a poorly understood part of the central USA Midcontinent. A principal result this study is that a prominent zone of high-amplitude dipping reflectors follows the western flank of the WVFS within the upper and middle Precambrian crust. Although reflectors in the upper crust maintain a west dip on both dip profiles (Fig. 3), the dip of middle crustal reflectors switches from mainly west on profile A (center part) to east on profile B. Reflector patterns in the upper and middle Precambrian crust are not vertically continuous and frequently show divergent trends (Fig. 3) giving the impression of a level of "detachment" that approximately corresponds to an upper-to-middle crust boundary. The observed middle crustal reflectors probably extend deeper into the lower crust (i.e., beneath km 25) since in all cases (profiles A, B, C) where prominent deep reflections are observed they extend to the bottom of the unmigrated 8-s record (e.g., Fig. 4b). Strike profiles (C and especially D) are characterized less by planar dipping reflections than by diffractive zones near the upper-to-middle crust boundary. The uniqueness of the dipping reflector zone along the WVFS can be appreciated by noting that on the 333-km east-west COCORP (Consortium for Continental Reflection Profiling) deep seismic reflection transect [*Pratt et al.*, 1989; 1992], shot across the Illinois basin in Indiana and Illinois in 1987 (Fig. 2), similar deep moderately dipping zones are not observed. This is despite the excellent data quality and the design of the acquisition parameters for imaging the deep crust. In fact, the anomalous dipping reflector zone beneath the WVFS contrasts with the nondescript horizontal crustal reflectivity that is characteristic of the Illinois basin to the north and west (Fig. 2; see also Figure 5 of *Pratt et al.* [1992]).

The WVFS has long been implicated as relating somehow to the seismogenic source in this region [*Mitchell et al.*, 1991]; however, another of our principal observations is that no obvious geometrical connection appears between the predominantly normal faults of the WVFS and the deep reflector structure (i.e., deep reflectors and normal faults in Paleozoic strata are not collinear). This general lack of relation allows two types of interpretation for the observed crustal reflectivity. Deep Precambrian volcaniclastic sequences have been interpreted from seismic reflection profiles in the USA Midcontinent, for example, the Proterozoic Keweenawan rifts in Kansas and Michigan [*Van Schmus and Hinze*, 1985; *Pratt et al.*, 1992]. It is conceivable that the deep reflectivity on the new profiles could represent stratified remnants of a deeply buried Precambrian sedimentary or volcaniclastic basin like observed elsewhere in the Midwest, perhaps locally deformed, and with a possible igneous component. The Precambrian Centralia sequence, however, does not correlate to the deep basement reflectivity on the new profiles. A recent study by *McBride and Kolata* [1999] maps the Centralia sequence in 3-D and shows where it wedges out and disappears as depicted in Figure 2. This is especially clear on profile C, which shows the Centralia sequence (km 0-35) as distinct from middle crustal reflections below and also from upper crustal dipping reflections just to the south (km 20-35). Thus the deep basement reflectors, if sedimentary, would be part of a previously unrecognized and even older Precambrian sequence. A sedimentary-volcanic origin is deemed admissible but not probable because (1) no stratigraphic sedimentary sequence-like geometries are observed (e.g., fanning of reflectors, pinch-outs; evidence of normal faulting), (2) the observed structural dips tend to be relatively high for a sedimentary succession, unless highly deformed; (3) the great depth of maximum burial (>25 km) would tend to argue against a basinal deposit (the Centralia sequence elsewhere reaches an estimated known maximum depth of 10 km [*McBride and Kolata*, 1999]).

A second possible explanation for the dipping reflector structure is that it may express compressional deformation (e.g., thrust faults). A thrust fault interpretation for the dipping basement reflectors is suggested by (1) their appearance in places beneath subtly arched Paleozoic reflectors (e.g., km 35-55, profile B; Fig. 6), (2) their association on profile A with bent and offset shallow basement reflectors above them (km 15-22, Fig. 4a), and (3) their occasional appearance beneath antiformal structures within the Precambrian crust (e.g., km 0-10, profile A (south part); km 20-35, profile C). The absence of a direct geometrical relation between the deeper, crustal structure and strong deformation in the Paleozoic section suggests that the crustal structure was originally produced by a pre-Appalachian stress, possibly the distal Grenville orogeny. The crustal structure was then slightly reactivated during the Paleozoic to produce the gentle arching (Fig. 6). Paleozoic reactivation of dipping structures in Precambrian basement has also been described from other reflection profiles in the Illinois basin [*McBride and Kolata*, 1999]. According to the model of *Hauser* [1996], the study area is located within the south-central portion of the "Midcontinent Microplate" (Fig. 8), defined mainly by the Proterozoic Keweenawan Midcontinent rift (~1.1 Ga, [*Davis and Paces*, 1990]) and by the Grenville orogenic front (995-980 Ma [*Krogh*, 1994]; 1150-900 Ma [*Van Schmus and Hinze*, 1985]). Therefore, one possible explanation for the dipping reflectors is that they represent compressional deformation associated with the Grenville orogeny, although we note that the Grenville front itself is hundreds of kilometers east of the reflectors (Fig. 8). It is conceivable that deformation could propagate far to the west in the Grenville foreland as has been shown by interpretations of seismic data by *Hauser* [1993] for western Ohio and by *Stark et al.* [1999] for southwestern Indiana. *Bear* [1997] has documented severe deformation, interpreted as Grenville, in the Precambrian basement of southern Indiana, on the eastern boundary of our study area. Dipping reflectors are not uncommon for Precambrian crust beneath much of central North America beyond the Illinois basin and are usually interpreted as compressional structures [*Green et al.,* 1988; *Pratt et al.,* 1989; *Culotta et al.*, 1990; *Drahovzal et al.*, 1992; *Hauser*, 1993] (Fig. 8).

6. A Precambrian Suture Zone?

We suggest that the zone of prominent dipping reflections and associated diffractions beneath the western flank of the WVFS represents a Precambrian suture zone. The dipping reflection-diffraction pattern is similar to that described for well-documented Paleozoic continental suture zones such as the buried Alleghanian suture in the southern Appalachians and the Iapetus suture offshore England [*Nelson et al.,* 1985; *Klemperer and Matthews*, 1987]. Using worldwide examples, *Sadowiak and Wever* [1990] argue that suture zones can be identified from a pattern of dipping reflections and associated diffractions in the crust (Fig. 9). This pattern bears a strong resemblance to the reflector-diffractor structure we observe beneath the WVFS (cf. Figs. 3 and 9). *McBride and England* [1999] demonstrate that steeply dipping compressional reflector structures on dip lines over the East Shetland platform (part of the Paleozoic Caledonian orogen) correspond to horizontal layers of diffractions on intersecting strike profiles, similar to the relations observed between dip profile B and strike profile D. The pattern of antiformal reflectors underlain by planar reflectors on profile B is similar to patterns observed in compressional orogens, especially suture zones (e.g., Fig. 9), and are interpreted as thrust anticlines [*Sadowiak and Wever*, 1990; *McBride and Nelson*, 1991; *Blundell*, 1993; *McBride and England*, 1999]. A compressional interpretation accords with the conclusions of *Bear et al.* [1997] that the WVFS had a significant dextral strike-slip component that probably reactivated older structure. Although the WVFS has traditionally been interpreted primarily as a zone of normal faulting [*Bristol and Treworgy*, 1979], *Nelson* [1995] has proposed that the faults originated from a deformation episode that produced a doming along a north-northeast-trending axis. The contrasting dips on individual and between profiles may indicate two distinct episodes of deformation; however, *Beaumont and Quinlan* [1994] have used geodynamic models of deformation in orogenic belts to suggest that contrasting reflector patterns like observed in our dip profiles can be produced by a single continuing process of compression to produce a dual thrust fault vergence. The non-continuity and distinct structure of upper and middle crustal reflectors may imply a preserved level of detachment. *Hall et al.* [1998] have interpreted an analogous reflector pattern from the Canadian Appalachians to represent a horizontal rheological contrast in the crust.

Our preferred interpretation of the prominent reflections themselves is that they represent faults or discrete shear zones. Reflections from inclined fault zones in the middle-to-lower crust have been recorded from many surveys, for example, the Wind River thrust in Wyoming [*Smithson et al.*, 1979], the Moine thrust offshore Scotland [*Snyder*, 1990; *McBride and England*, 1994], and the Grenville Front in Ontario and Ohio [*Green et al.*, 1988; *Culotta et al.*, 1990] (see *Cook and Varsek* [1994] for a review of the origin of dipping crustal reflectors). Fracturing, fault gouge and enhanced pore pressure are ways in which the reflection coefficient can be increased enough to produce a bright reflection. *Jones and Nur* [1984] concluded that deep crustal reflections are produced by the highly anisotropic mylonites that formed in what was originally the ductile part of a fault zone [*Sibson*, 1977]. Mylonites involve grain size reduction and a strong fabric created by ductile deformation of quartz, phyllosilicates, and other minerals. Direct field observations [*Hurich et al.*, 1985] confirm mylonites to be reflective. Deep reflectivity within fault zones could also be caused locally by enhanced pore pressure. The excess fluid could be provided by mineral dehydration brought on by anomalous stresses and shearing. *Jones and Nur* [1982] suggest that, for a lithostatic pore pressure, a seismic velocity decrease of 11% is possible. It is also possible that the reflectivity was enhanced by local tubular intrusion of mafic igneous rocks [e.g., *Pratt et al.*, 1991].

7. Seismicity

The WVSZ and surrounding area of Illinois, Indiana, and Kentucky have been rated to have a high seismic hazard (Fig. 1) [*Frankel*, 1995] so any information on crustal structure here would be useful in providing geometrical constraints on the possible seismogenic source. Most seismic events in the WVSZ are either too old or too small to yield information on their source parameters. Profile A fortuitously passes 4.9 km northeast of the 1968 epicenter (1968.11.09 m_{bLg}=5.5), based on the relocation study of *Gordon* [1988] (Fig. 2). Interestingly, the strongest and most prominent dipping reflector zone is located near the 1968 earthquake (Fig. 4a). The 1968 event is significant as an intraplate earthquake in that it is the largest and one of the deepest 20th century earthquakes in the central USA Midcontinent. The earthquake, situated 10-20 km northwest of the WVFS, represents the contemporary stress system [*Taylor et al.*, 1989]. *Stauder and Nuttli* [1970] interpreted the focal mechanism of this event to be consistent with a NNE-striking, west-dipping reverse fault. Because of the attention focused on this event, several depth estimates have been stated in the literature [*Wheeler and Johnston*, 1992]. For this study we use as a reference the generally accepted estimate of 21.2±5.4 km based on the "joint hypocenter determination" technique [*Gordon*, 1988; see also *Langer and Bollinger*, 1991]. Earlier depth estimates gave more precise values that fall within the lower limits of this range (e.g., 25±2 km by *Stauder and Nuttli* [1970] based on depth phases). Depth estimates at the upper limits of this range are 22±2 km by *Herrmann* [1979] based on surface wave amplitude modeling and 19 km by *Gordon et al.* [1970] using routine techniques (see *Wheeler and Johnston* [1992] for review).

Using the most conservative estimate of 21.2±5.4 km [*Gordon*, 1988], the hypocenter plots near the upper surface of the 0.8-s thick band of brightest reflections (or 2.5-km thick using 6.2 km s^{-1} as a conversion velocity). *Herrmann's* [1979] depth estimate of 22±2 km more precisely places the hypocenter within the center of this band. The lengths of the axes of the nominal 95% confidence interval ellipse (Fig. 2) are such that it is statistically possible that the hypocenter could project just to the northwest or southeast of the west-dipping reflectors (Fig. 4a). In any case, given the size and depth of the individual deep reflectors on profile A and the fact that they form part of a regionally extensive zone that persists for at least 40 km from northeast to southwest along the WVFS projecting toward the 1968 epicentral region, it seems probable that the middle crustal reflectors on profile A would continue through the area underlying the ellipse (Fig. 2). Projecting the hypocenter perpendicular to the line of the profile places it within the prominent west-dipping reflections as shown in Figure 4a. Alternatively, if we project according to the N

15° E-striking nodal plane, the hypocenter appears 1.6 km farther to the northwest along the line, still within the dipping reflector package; however, given the level of uncertainty in location, it is not possible to distinguish the two possibilities, which are only slightly different. After the 1978 seismograph network installation, three better-located events (1978.06.02, 1978.12.05, 1980.03.13; Table 1) in the study area occurred with focal depths in the 20-25 km depth range [*Gordon*, 1988]. The most accurately located of these is the 1980 event with a computed focal depth of 20.3±1.8 km and m_{bLg}=3.0 [*Gordon*, 1988; *Langer and Bollinger*, 1991]. The epicenter is within a few kilometers of that of the 1968 event and the two hypocenter depths are almost indistinguishable. The close proximity of the two earthquakes and the recording of 5 aftershocks of the 1968 event in the epicentral region of magnitude (m_b) up to 4 at about the same depths as the main shock [*Stauder and Pitt*, 1970] suggest a possible zone of weakness.

The original interpretation by *Stauder and Nuttli* [1970], that the west-dipping nodal plane is the reverse fault, was based on the fact that the westernmost normal faults of the WVFS are upthrown to the west. The focal mechanism solution for the 1968 earthquake (Fig. 1) indicated nodal planes striking at N15°E dipping 45° W and at N01°W dipping 47° E [*Stauder and Nuttli*, 1970]. The nodal planes would be expressed on the vertical plane corresponding to profile A with apparent dips of 43° and 41°, respectively. Both west- and east-dipping reflectors appear in the middle crust in the general vicinity of the projected hypocenter, although west dips dominate and are closest to the hypocenter.

8. Implications for the Seismogenic Source in the Wabash Valley Seismic Zone

Due to the spatial association of the 1968 hypocenter and the west-dipping reflector zone, and due to the fact that the west-dipping reflectors overwhelmingly dominate the area of profile A, we suggest as a working hypothesis that the west-dipping nodal plane is the fault plane, as inferred by *Stauder and Nuttli* [1970], and that the west-dipping reflectors may be associated with the zone of recently active faulting. The greater dip of the actual rupture plane (43°, apparent; Fig. 4a)) relative to the observed reflector dip (21°) may be related to the inability of the survey to image steep (e.g., >40°) dips. The observed reflector dip is probably close to true dip, assuming that the reflector strikes close to parallel with the WVFS, as does the overall reflection zone. This dip is also falls within the range of dips observed elsewhere in the middle crust on the profiles. Increasing the migration interval velocity beyond a certain point (Fig. 4b) produces almost no effect on the dip; increasing the velocity used for time-to-depth conversion from 6.2 km s^{-1} to 7.0 km s^{-1} (an upper limit), increases the dip to 25°. A possible, geological, explanation for the discrepancy is that structural complexities in the vicinity of the rupture may not be resolvable on the reflection record. This would be especially true if the contemporary rupturing was related to a splaying off the more developed (and geologically older) fault surface. On a deep seismic reflection profile over the Sierras Pampeanas (western Argentina), *Snyder et al.* [1990] noted hypocenters with nodal planes that were steeper by several degrees than nearby dipping basement reflections interpreted as thrust faults at depths centered around 15 km. They interpreted this discrepancy to mean that earthquakes were occurring along steeper subsidiary faults associated with the imaged shallower dipping reflectors. In a well-constrained example from the Coalinga Hills east of the San Andreas fault (California Coast Ranges), aftershocks and the main shock of the Coalinga 1982-1985 earthquake sequence mostly occur along or near the steeper portions of thrust faults (Fig. 10) as mapped from reflection data [*Wentworth and Zoback*, 1989]. Studies based on the Northridge 1994 earthquake aftershocks [*Carena and Suppe*, 1999] indicate that the thrust fault geometry is very 3-D. Our suggested interpretation for the 1968 event is somewhat analogous to the above examples in that earthquakes could nucleate along thrust splays or up-turned portions of the fault zone that steepen upward from the shallower dipping reflectors (Fig. 11). In the original tectonic interpretation of the 1968 event in Illinois, *Stauder and Nuttli* [1970] proposed that the faults controlling the earthquake may steepen with decreasing depth.

In the central NMSZ, seismicity is expressed as a discrete planar distribution of hypocenters in the upper crust (5-14 km depth; *Chiu et al.* [1992]) that defines a 23°-32° west-dipping thrust fault within a left-stepping restraining bend in dextral strike-slip faulting [*Schweig and Ellis*, 1994] (Fig. 1). In contrast, no analogous seismogenic source structure has been previously recognized in the WVSZ to the north. The complex structural zone in the upper and middle crust along the western flank of the WVFS involves reflector apparent dips like those for thrust events in the NMSZ (Fig. 1). Compared with results of previous reflection profiling in the Illinois basin, the reflector zone stands out as being unique. The implication of a possible correlation of the reverse fault focus with a coherent planar reflector pattern in the middle crust would be that contemporary stress is being released by the reactivation of ancient (i.e., Precambrian and/or Paleozoic) structures. This reactivation could involve slip along faults represented directly by the large planar reflectors or by steeper structures closely associated with them. A similar interpretation was put forward for earthquakes beneath the Appalachian Piedmont just east of the Blue Ridge thrust front in the central Virginia seismic zone projected onto the plane of a regional deep seismic reflection profile [*Çoruh et al.*, 1988]. In their study, antiformal compressional structure and hypocenters with a mixture of reverse and strike-slip focal mechanisms, both associated with dipping crustal reflectors originally Paleozoic in age, were interpreted as reactivated thrust faults (Fig. 12). Recent examples of thrust-fault-generated earthquakes that were associated with an overlying fault-propagation fold are the 1980 El Asnam (Algeria) and the 1994 Northridge (California) events [*King and Yielding*, 1984; *Davis and Namson*, 1994]. These examples may be analogous to our interpretation of the 1968 event (Fig. 11) in that thrusts occur beneath pre-existing antiforms or bends in overlying reflectors.

It is well known that seismic moment scales with earthquake rupture parameters (see *Wang and Ou* [1998] and *Wells and Coppersmith* [1994] for review), although the relation varies for different types of earthquakes and for different regions [*Scholz et al.*, 1986]. *Johnston* [1993; 1996] has quantitatively related the seismic moment magnitude of earthquakes in "stable continental regions" to various earthquake source parameters (Fig. 13). On this basis, the 1968 main shock was caused by a rupture with a length and width of ~2.9 km that slipped ~44 cm. The length of reflection segments observed from the middle crust on the migrated section of profile A varies between 1.0 and at least 3.0 km. These lengths are comparable to those of reflectors associated with hypocenters in the central Virginia seismic zone, which ranged between 1.5 and 4.0 km (Fig. 12). The dimensions of the 1968 rupture zone (Fig. 11) are comparable to the observed length of the bright reflection segments near the hypocenter (Fig. 4a). Alternatively, the observed thrust reflectors may not have been reactivated *sensu strictu*, but instead a general zone of crustal weakness (earlier faulting), constituted in part by the reflectors, in which contemporary earthquakes are concentrated. The higher angle of the 1968 rupture may have thus cut across the old Precambrian faults, which make up a stress concentration.

9. Conclusions

Although the Illinois basin is one of the world's most intensively studied sedimentary basins [*Leighton*, 1996], little is known about deeply buried structures that influence earthquake location. An extensive series of moderately dipping crustal reflectors appear below the western flank of the WVFS. A compressional suture zone interpretation can explain the various characteristics of the reflector zone in the crust (e.g., dipping reflections, diffractive zones, antiformal patterns), while providing a framework in which to understand better the seismogenic source in the WVSZ. The presence of strongly developed deep structure beneath undeformed or very gently deformed Illinois basin Paleozoic strata imply a Precambrian age (possibly Grenville). However, the association of dipping crustal reflectors and gently arched Paleozoic strata also hint at a limited degree of Phanerozoic reactivation.

Within the central Midcontinent, earthquakes appear to cluster in depth over a "shallow" (5-15 km) and "deep" (20-25 km) range, possibly indicating a weak intervening horizontal aseismic zone in the crust [*Chen*, 1988; *Wheeler and Johnston*, 1992]. The top of this intervening aseismic zone (~15 km) matches approximately the depth of the "detachment" level across which reflector structure is discontinuous and changes in style (Fig. 3). The "deep" zone corresponds approximately to the interval containing the most prominent dipping reflectors. Earthquakes occurring in the "shallow" zone are dominantly high-angle strike slip (e.g., 1974 and 1987) as opposed to low-angle reverse (e.g., 1968) (Table 1) [*Taylor et al.*, 1989]. The disparity in structure between the upper and middle crust may influence the vertical partitioning of contemporary strain in the WVSZ, especially if pre-existing dipping fault zones (e.g., blind thrusts) are providing a fabric for reactivation.

Because the 1968 focus is spatially associated with the most prominent reflector structure (i.e., where deformation is inferred to have been greatest over geologic time), we suggest that the 1968 event, subsequent aftershocks, and possibly the nearby 1980 event (Fig. 1) reactivated these structures. The significant-magnitude instrumental and historic earthquakes in southeastern Illinois centered around the Wabash River valley, as well as the paleoliquefaction sites in this region attributed to strong shaking [*Obermeier,* 1998], imply a major seismic zone that may approach [*Langer and Bollinger*, 1991] the earthquake hazard of New Madrid (Fig. 1). Indeed, the paleoliquefaction research implies that the strongest prehistoric earthquakes in the WVSZ were associated with tectonic source zones in the immediate area of this study [*Obermeier et al.*, 1996].

A long-standing paradigm in the North American stable continental region is that earthquakes here tend to occur by reactivation of existing faults [*Hamilton*, 1981; *Marshak and Paulsen*, 1996]. Faulted rock is weaker than unfaulted rock, and, even if an ancient fault is healed, the healed fault rock is likely to retain a strong planar fabric that would represent a weak orientation if the fabric is optimally oriented in the ambient stress field [e.g., *Wheeler and Johnston*, 1992]. If the package of dipping reflectors on profile A represents the sheared rock of a fault or fault zone, then the fabric of the fault rock, healed or not, will be geometrically related to the dipping reflectors. Both the dipping reflectors and one nodal plane of the 1968 earthquake are well oriented for slip in the ambient stress field, as is the north-to-northeast trend of the reflector zone in plan view (Figs. 1 and 3). Our observation that middle crustal reflectors dip at a shallower angles than those of earthquake nodal planes may mean that deep WVSZ earthquakes are nucleating along subsidiary structures, too steep to be imaged directly, but closely related to the shallower dipping reflector fabric. At the scale of the earthquake's 2.9-km-long rupture zone, it is possible that an undetected weak surface or zone exists inside, but is structurally related to, the package of dipping reflectors but is oriented at a large angle to the reflectors (Fig. 11). Accordingly, one possible explanation of the 1968 earthquake is that it occurred by reactivation of an ancient fault within the package of dipping reflectors, which act as a stress concentration.

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FIGURE CAPTIONS

Figure 1. Central U. S. earthquakes through 1995 of body wave magnitude of at least 2.0. Sources: (1) the "Catalog of Central US Earthquakes, 1810-1980" [*Nuttli and Brill*, 1981]; (2) instrumental data from the Central Mississippi Earthquake Catalog, June 29, 1974 through December 31, 1995 as compiled by the St. Louis University Regional Seismic Network. Moderate magnitude events in the range 5.0-5.9 are shown by 's. Surface-wave focal mechanisms are plotted from *Taylor et al.* [1989]. Two pairs of arrows represent contemporary maximum horizontal stress directions [*Nelson and Bauer*, 1987; *Kolata and Nelson*, 1991]. Also shown are contours showing seismic hazard surrounding the New Madrid seismic zone as peak acceleration (%g) with a 10% probability of exceedance in 50 years (site: NEHRP B-C boundary) [*Frankel*, 1995]. Note that the innermost, 12% contour approximately defines the New Madrid seismic zone. Schematic cross-section through the center of the left-stepping bend (i.e., transverse zone) in the New Madrid seismic zone (locally, the Lake County uplift (LCU)) based on information from earthquake focal mechanism solutions and hypocentral locations [see *Chiu et al.*, 1992; *Pratt*, 1994].

Figure 2. Map of the south-central Illinois basin and Wabash Valley fault system (WVFS), with structure contours (feet below sea level, contour interval is 100 feet (~30.5 m)) on the base of Upper Devonian New Albany Shale (modified from *Cluff et al.* [1981]), known fold axes, faults, and other structures [*Nelson,*

1995], and revised, instrumentally recorded epicenters ($m_{bLg}\geq3.0$) with nominal 95% confidence ellipses [*Gordon*, 1988; *Langer and Bollinger*, 1991]. Limit for the Centralia seismic sequence is from *McBride and Kolata* [1999]. Also shown is the location of the COCORP deep seismic reflection profile, Illinois Line 1 (VP is vibrator point). A, B, C, and D refer to reflection profiles reprocessed for this study. RCSFZ is Rough Creek Shawneetown Fault Zone; LCFZ is Lusk Creek Fault Zone; MCA is McCormick Anticline; NBA is New Burnside Anticline; CGFS is Cottage Grove Fault System; RLFZ is Rend Lake Fault Zone; BNS is Bogata-Rinard Syncline; CCA is Clay City Anticline; CM is Charleston Monocline. ARFZ is Albion-Ridgway Fault Zone; RG is Ridgway Graben; IF is Inman Fault; IEF is Inman East Fault; HPFZ is Herald-Phillipstown Fault.

Figure 3. Perspective simplified line drawing of migrated profiles as reprocessed in this study. Profiles are shown vertically exaggerated with arrows indicating principal dip directions for deep Precambrian reflectors. WVFS is Wabash Valley fault system.

Figure 4. **(a)** Line drawing interpretation of migrated seismic profile A. "Basal Reflector" marks the bottom of a shallow basement sequence. Three arrows show the three sets of west-dipping reflections. Small box shows apparent dip of west-dipping nodal plane for the 1968 event (interpreted as the fault plane) and its modeled rupture length. No vertical exaggeration for 6.2 km s^{-1}. Mechanism from *Stauder and Nuttli* [1970]. For this and subsequent illustrations of profiles A, B, and C only the principal stratigraphic markers are shown for the mostly horizontal Illinois basin Paleozoic sequence. **(b)** Migration spectra for portion of profile A, center part.

Figure 5. Detailed line drawing excerpt of profile B over the WVFS showing faulting of shallow Precambrian basement dipping reflector sequence. Arrows indicate prominent dipping reflections referred to in the text. NA is base of Devonian New Albany Shale Group; Kx is base of the Cambrian-Ordovician Knox Group; Pc is the interpreted top of Precambrian basement; CS is the base of the "Centralia sequence" [*Pratt et al.,* 1992] (stratigraphy applies to other lines as well). (see Figure 2 for location). No vertical exaggeration for 6.2 km s^{-1}. WVFS is Wabash Valley fault system.

Figure 6. Highly exaggerated versions of profiles A (north and center parts) and B showing relation of basement dipping reflections to subtle doming beneath the Wabash Valley fault system (WVFS).

Figure 7. **(a)** Unmigrated seismic reflection profile D displayed as a variable area section (see Figure 2 for location). No vertical exaggeration for 6.2 km s^{-1}. Arrows and letters indicate prominent diffraction zones referred to in the text. **(b)** Migrated version of profile D.

Figure 8. Map showing Midcontinent rift system (MCR) and Grenville Front tectonic zone (GFTZ) [*Van Schmus et al.*, 1993] and its possible southwest extension [*Hauser*, 1996]. Arrows are from *Hauser's* [1996] speculative model for the opening of the MCR and its relation to the GFTZ. The arrows indicate

the possible translation and rotation of the "Midcontinent Microplate" away from the MCR. The stipple pattern shows the postulated continuation of the MCR, which was overprinted by the younger tectonism of the GFTZ [*Hauser*, 1996]. The central part of the MCR, dominated by mafic igneous rocks, is black area; Duluth Gabbro is horizontal ruling; post-rift basins flanking the central MCR, filled mainly with clastic sediments, are shown by shaded area.

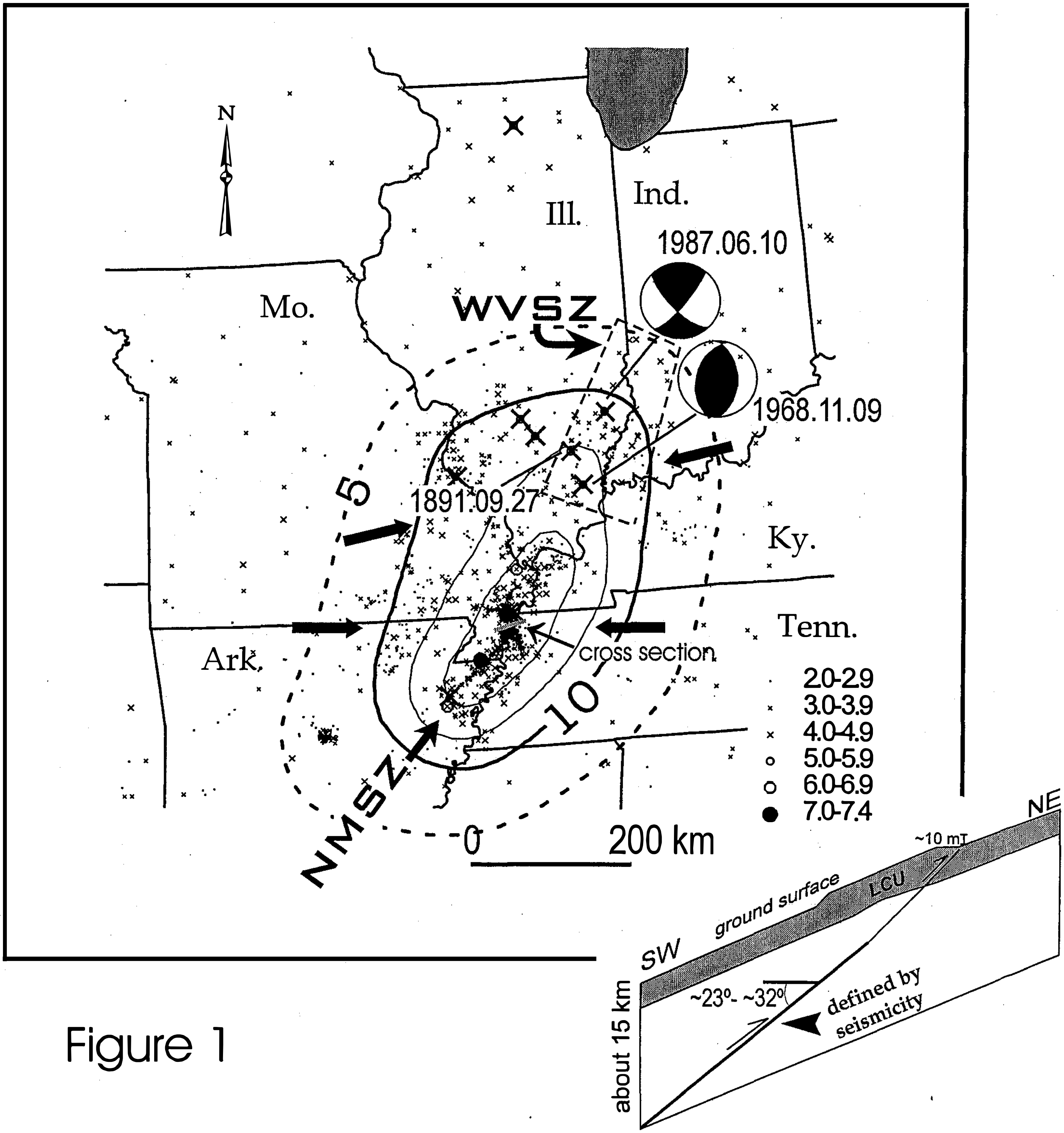
Figure 9. Idealized pattern of reflections and associated diffractions for a continental suture zone (unmigrated traveltime section) based on examples of well-documented Paleozoic suture zones from North America and Europe (modified from *Sadowiak and Wever* [1990]).

Figure 10. Structural cross section (based mainly on reflection data) across the Coalinga anticline, California showing mainshock and aftershocks of the 1983 Coalinga earthquake. Figure modified from *Wentworth and Zoback* [1989] and *Stein and Ekstrom* [1992].

Figure 11. Interpretive model corresponding to area of Figure 4a. Dashed lines are speculative. No vertical exaggeration implied. Interpretation of Rough Creek graben, whose main Cambrian normal fault was reactivated during later compression, is from *Kolata and Nelson* [1997]. Moho discontinuity is from *Allenby and Schnetzler* [1983].

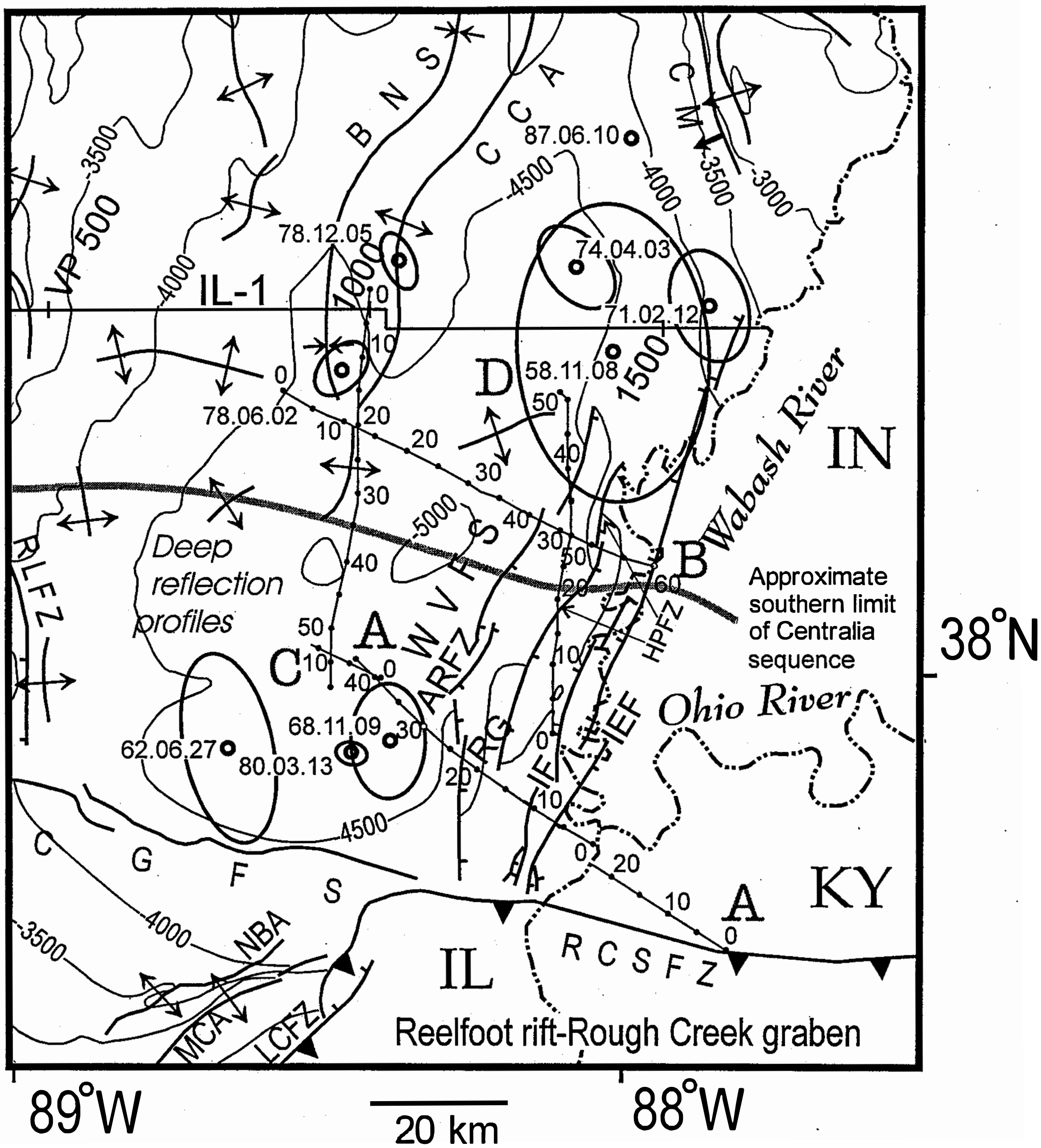
Figure 12. Simplified cross-section of correlation of earthquake hypocenters in the central Virginia seismic zone projected onto the interpreted "I-64" deep seismic reflection stacked section (modified from *Çoruh et al.* (1988)). "DS" is dike swarm. Excerpt shows portion of actual data with earthquake hypocenters superimposed (modified from *Pratt et al.* [1988]).

Figure 13. Earthquake source parameters estimated from constant stress drop by *Johnston* [1993; 1996] for intraplate regions. "Length" and "width" refer to the dimensions of the rupture zone. For the 1968 event, the length=width is about 2.9 km, which is comparable to the length of the reflectors near the hypocenter (see Fig. 4a), and the slip is about 44 cm.



N
Ill.
Ind.
Mo.
Ky.
Tenn.
Ark.
1987.06.10
1968.11.09
1891.09.27
WVSZ
NMSZ
5
10
cross section
2.0-2.9
3.0-3.9
4.0-4.9
5.0-5.9
6.0-6.9
7.0-7.4
0
200 km
SW
NE
ground surface
LCU
~10 m
about 15 km
~23°- ~32°
defined by seismicity

Figure 1



B N S
C C A
C M
87.06.10
-3500
-4500
4000
3500
-3000
VP 500
78.12.05
74.04.03
4000
IL-1
1000
71.02.12
D
58.11.08
1500
Wabash River
78.06.02
IN
Deep reflection profiles
-5000
W V H S
B
Approximate southern limit of Centralia sequence
RLFZ
HPFZ
A
C
ARFZ
Ohio River
68.11.09
62.06.27
80.03.13
4500
IEF
A
KY
C G F S
4000
NBA
-3500
IL
R C S F Z
MCA
LCFZ
Reelfoot rift-Rough Creek graben
38°N
89°W
20 km
88°W

Figure 2

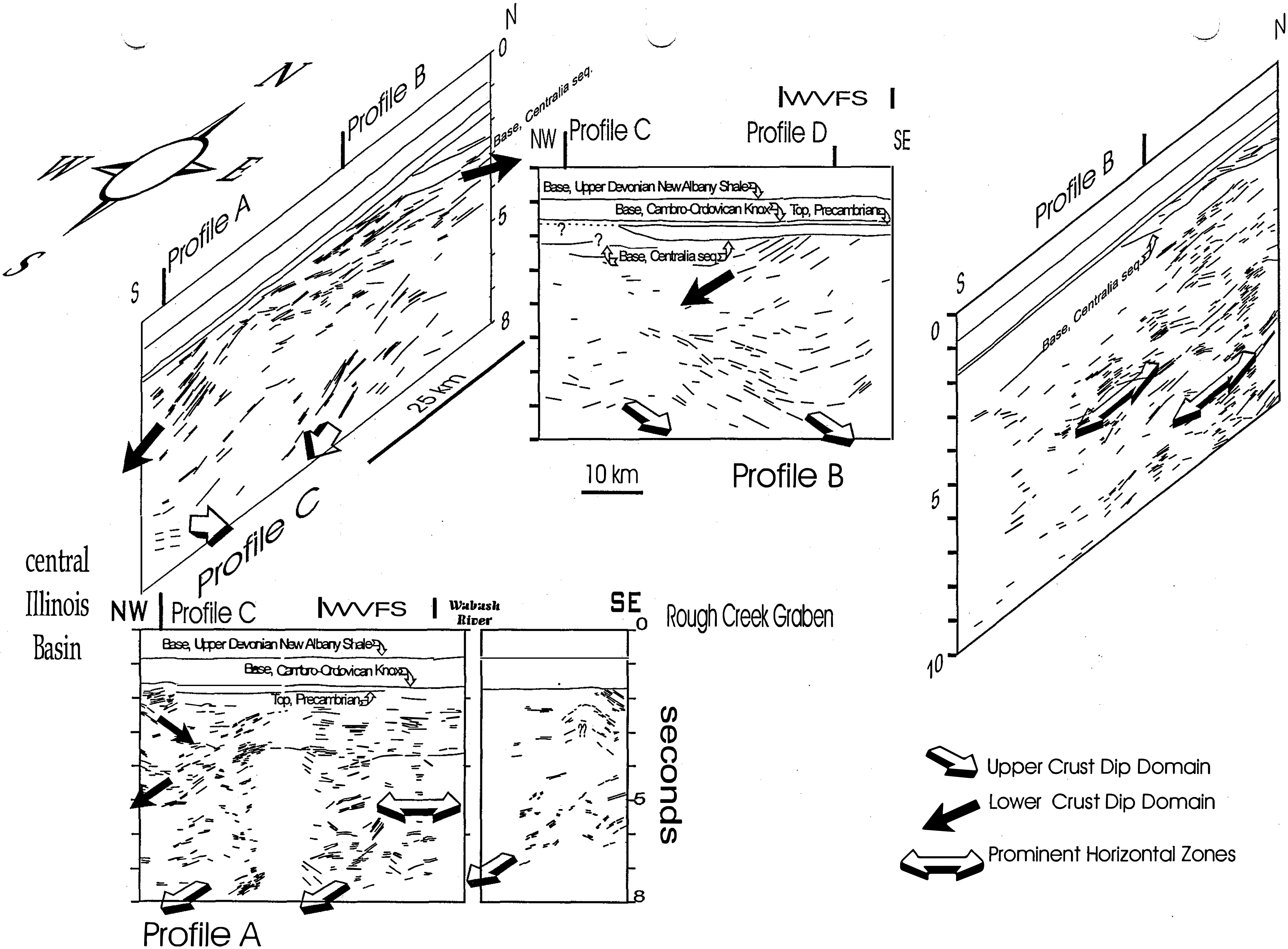
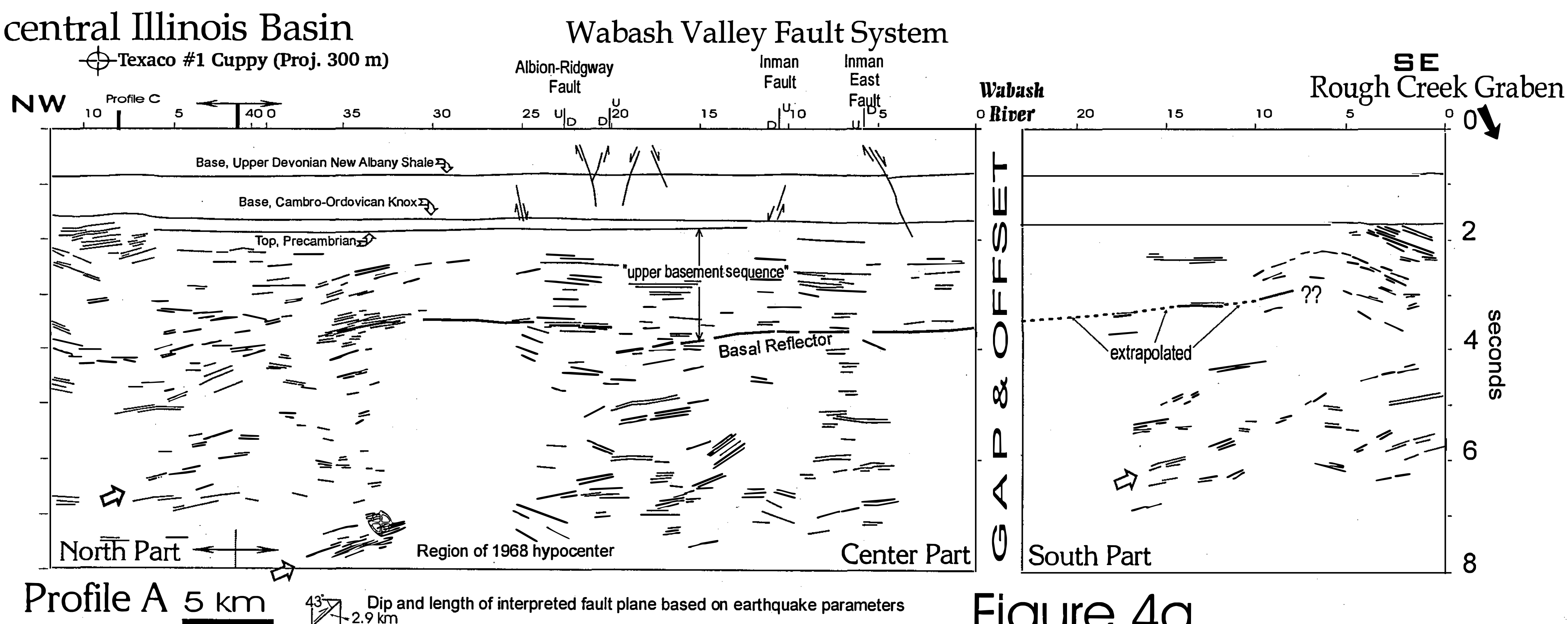

N
S
W
E
Profile A
Profile B
Profile C
Base, Centralia seq.
25 km
0
5
8
NW
SE
WVFS
Profile D
Base, Upper Devonian New Albany Shale
Base, Cambro-Ordovican Knox
Top, Precambrian
Base, Centralia seq.
10 km
Profile B
central Illinois Basin
Wabash River
Rough Creek Graben
seconds
Upper Crust Dip Domain
Lower Crust Dip Domain
Prominent Horizontal Zones
10

Figure 3



central Illinois Basin
Texaco #1 Cuppy (Proj. 300 m)
Wabash Valley Fault System
Albion-Ridgway Fault
Inman Fault
Inman East Fault
Wabash River
SE
Rough Creek Graben
NW
Profile C
Base, Upper Devonian New Albany Shale
Base, Cambro-Ordovican Knox
Top, Precambrian
"upper basement sequence"
Basal Reflector
GAP & OFFSET
extrapolated
??
seconds
North Part
Region of 1968 hypocenter
Center Part
South Part
Profile A
5 km
43°
2.9 km
Dip and length of interpreted fault plane based on earthquake parameters

Figure 4a

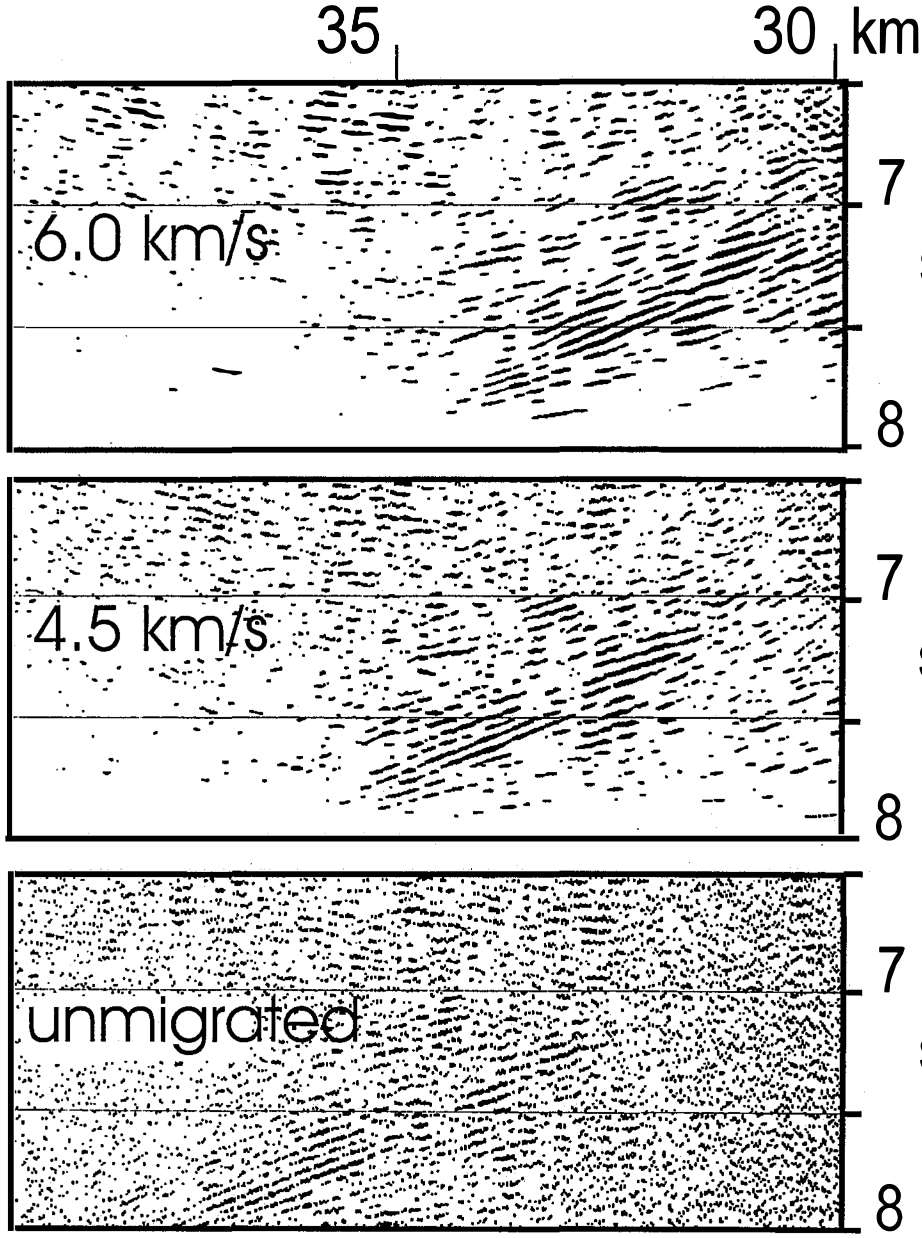


Figure 4b

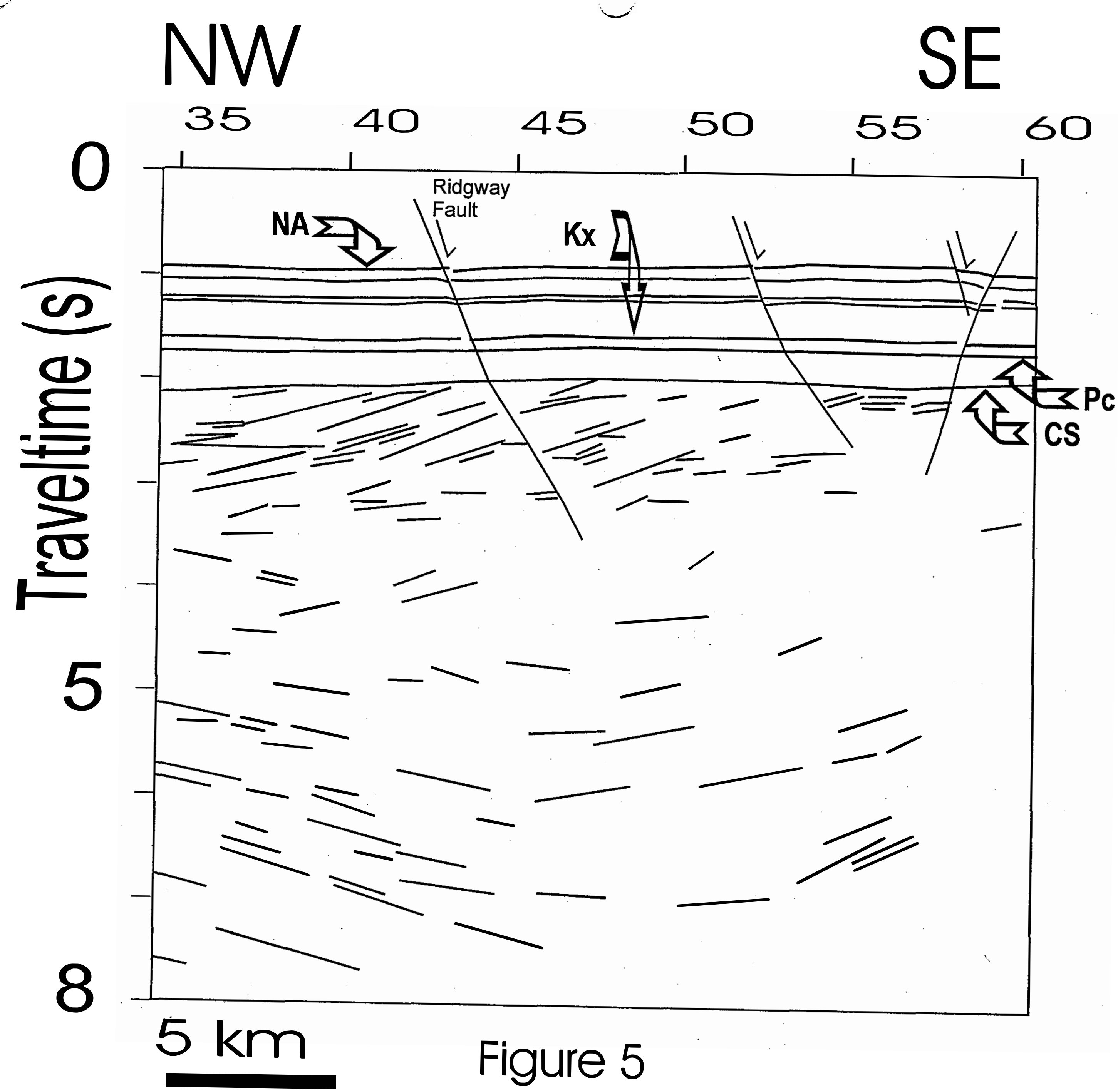

NW
SE
35
40
45
50
55
60
0
5
8
Traveltime (s)
Ridgway
Fault
NA
Kx
Pc
CS
5 km

Figure 5

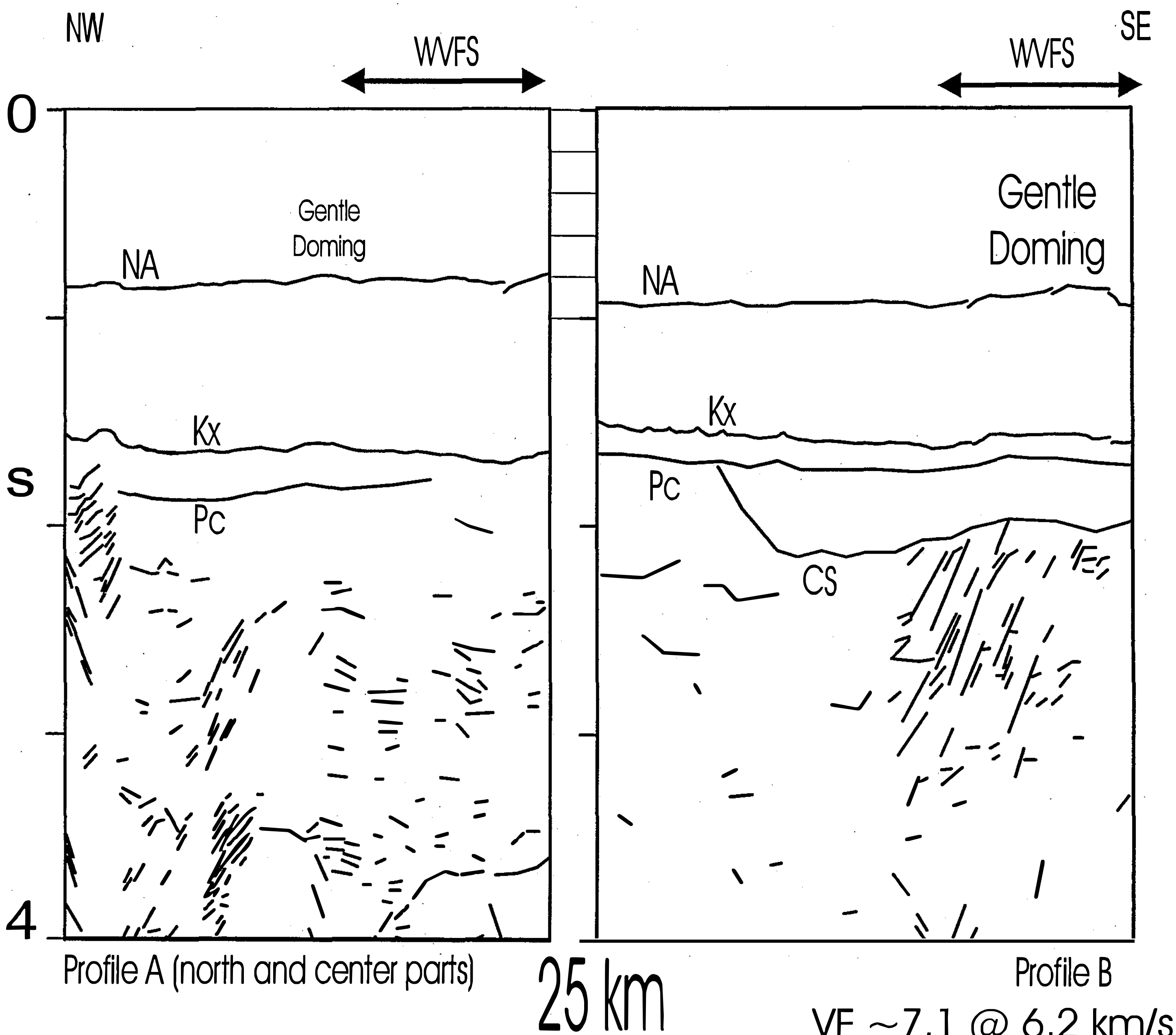

NW
SE
WVFS
WVFS
0
s
4
Gentle Doming
Gentle Doming
NA
NA
Kx
Kx
Pc
Pc
CS
Profile A (north and center parts)
Profile B
25 km
VE ~7.1 @ 6.2 km/s

Figure 6

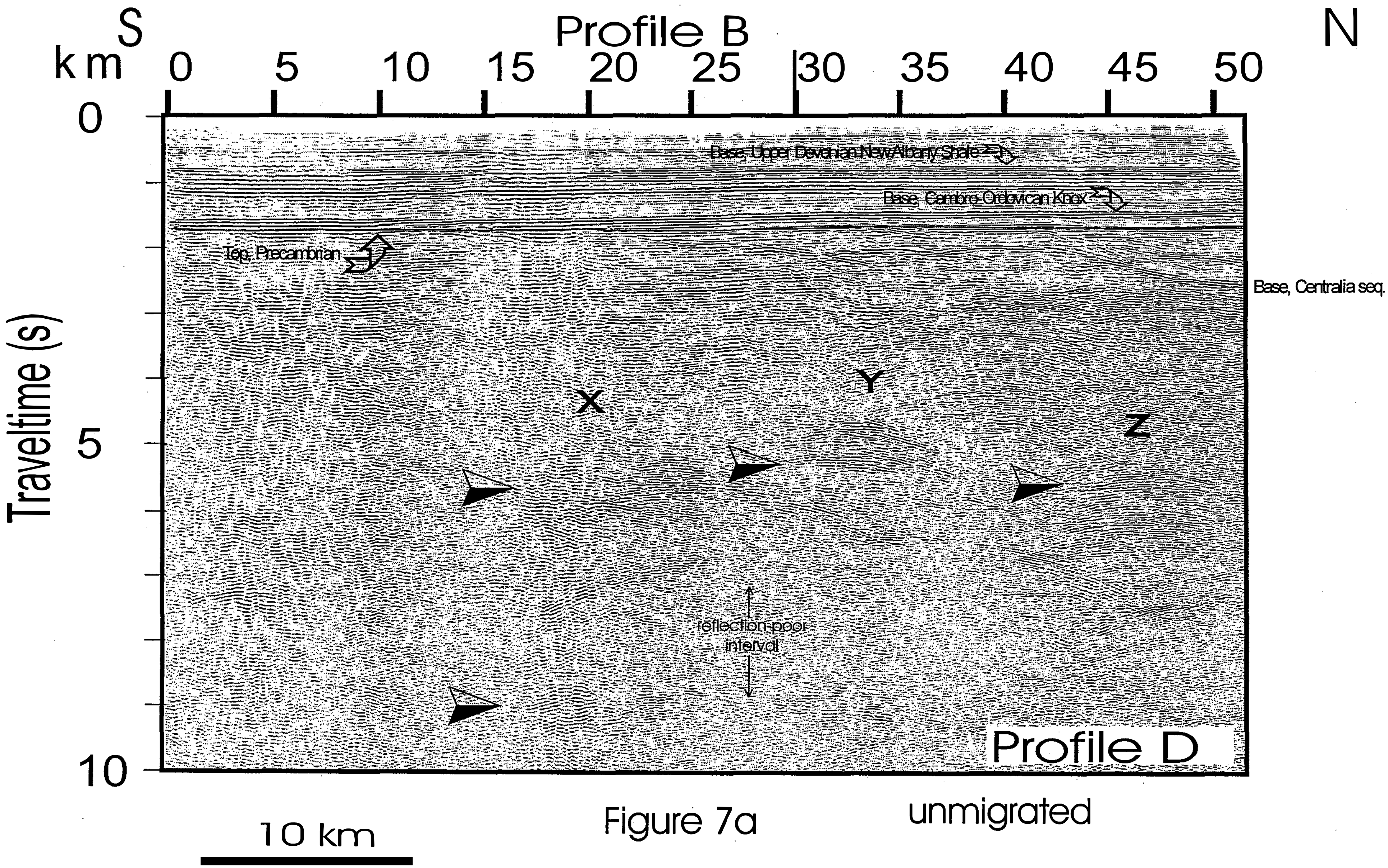

S
N
Profile B
km
0
5
10
15
20
25
30
35
40
45
50
Traveltime (s)
0
5
10
Base, Upper Devonian New Albany Shale
Base, Cambro-Ordovician Knox
Top, Precambrian
Base, Centralia seq.
X
Y
Z
reflection-poor interval
Profile D
10 km
unmigrated

Figure 7a

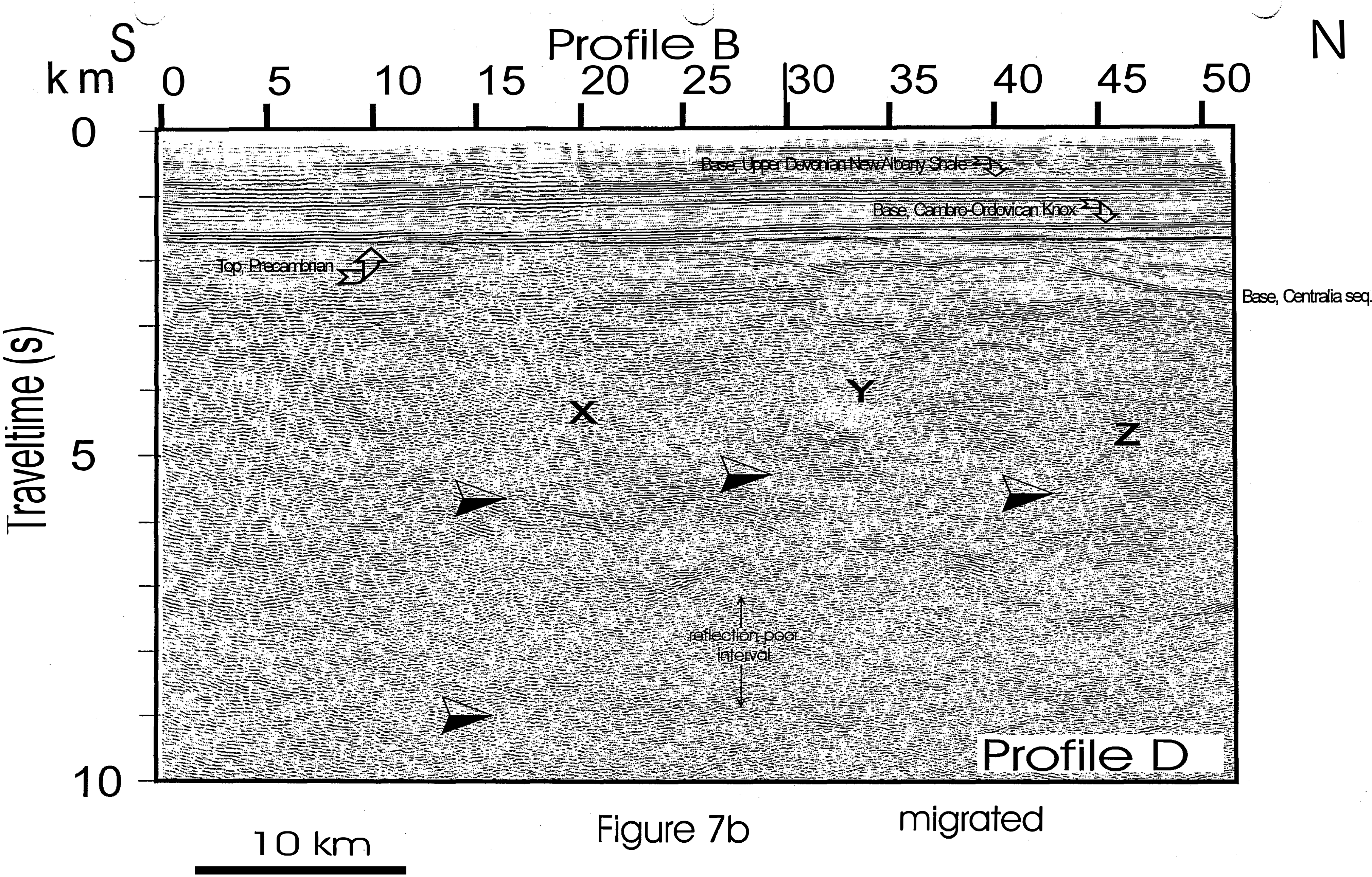
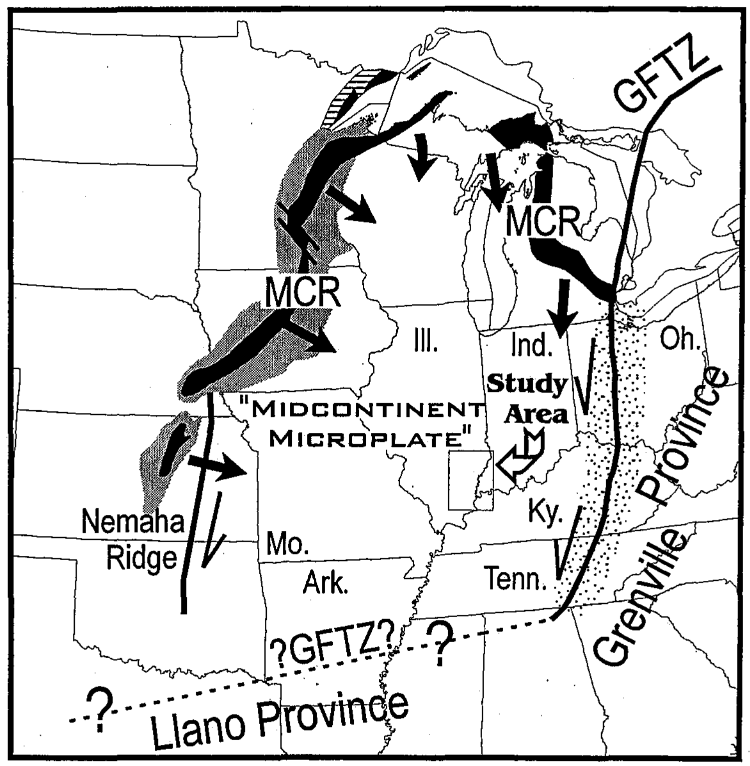


Figure 7b

migrated



GFTZ
MCR
MCR
Ill.
Ind.
Oh.
Study Area
"Midcontinent Microplate"
Province
Nemaha Ridge
Mo.
Ky.
Ark.
Tenn.
Grenville
?GFTZ?
?
?
Llano Province

Figure 8

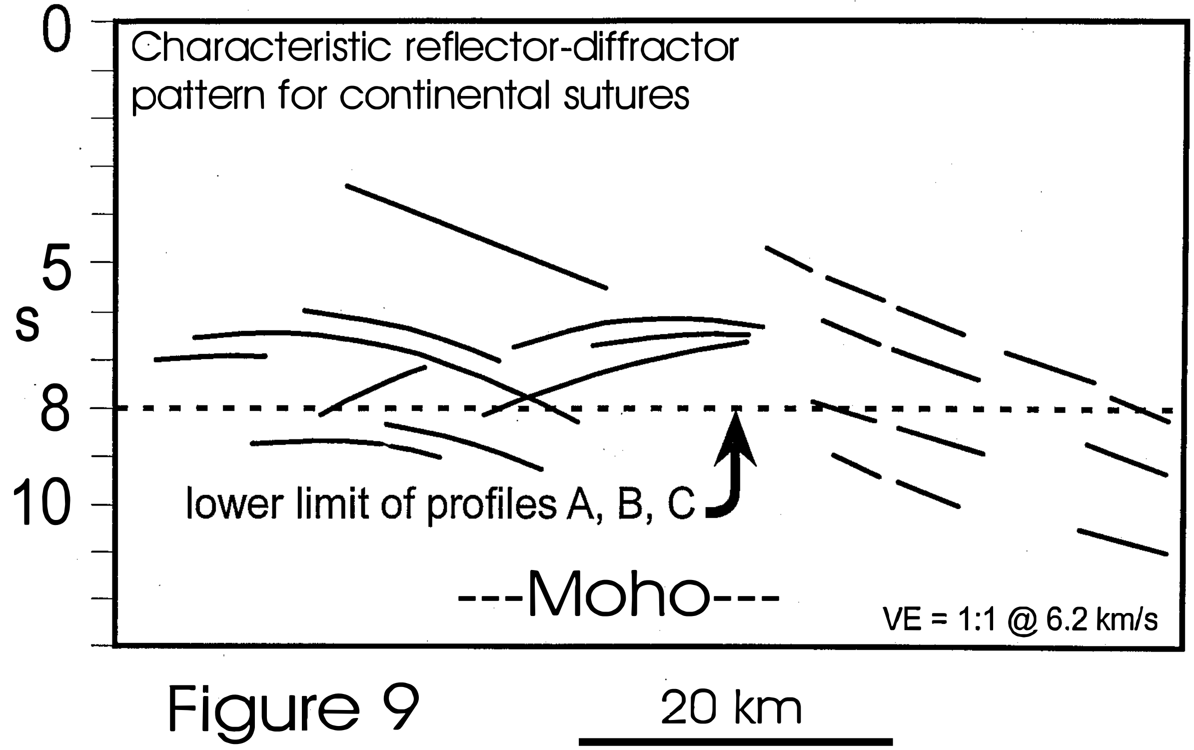

0
5
s
8
10
Characteristic reflector-diffractor pattern for continental sutures
lower limit of profiles A, B, C
---Moho---
VE = 1:1 @ 6.2 km/s
20 km

Figure 9

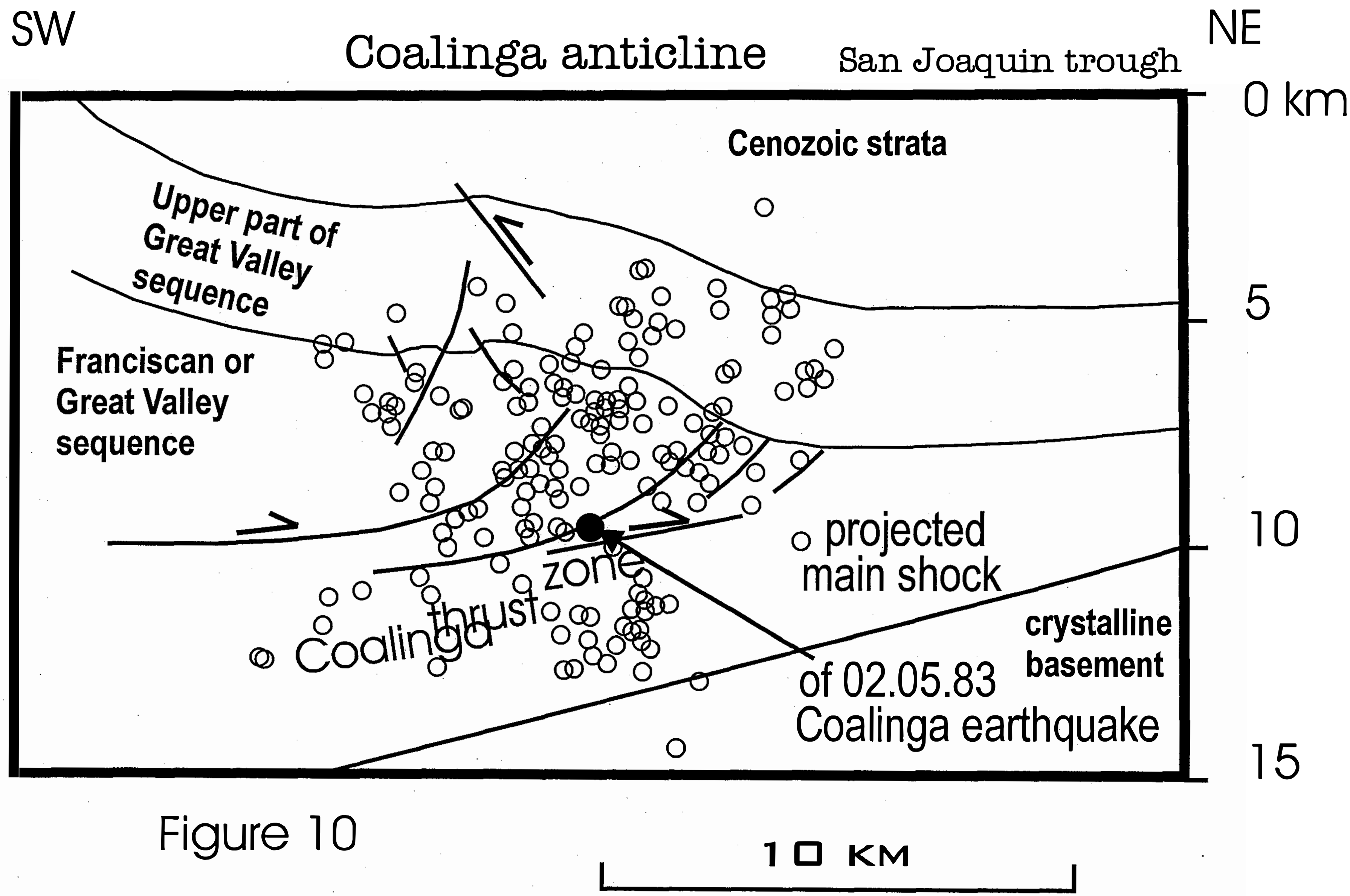

SW
NE
Coalinga anticline
San Joaquin trough
0 km
5
10
15
Cenozoic strata
Upper part of Great Valley sequence
Franciscan or Great Valley sequence
Coalinga thrust zone
projected main shock of 02.05.83 Coalinga earthquake
crystalline basement
10 KM

Figure 10

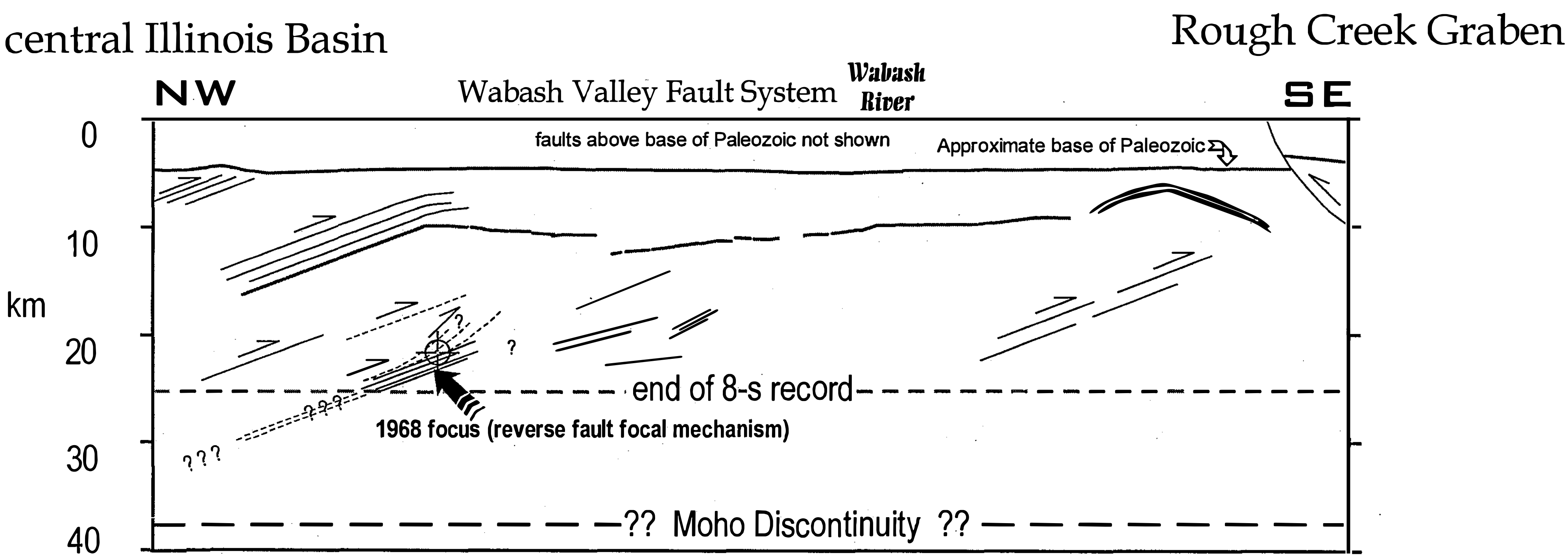

central Illinois Basin
Rough Creek Graben
NW
Wabash Valley Fault System
Wabash River
SE
0
10
20
30
40
km
faults above base of Paleozoic not shown
Approximate base of Paleozoic
end of 8-s record
1968 focus (reverse fault focal mechanism)
???
?? Moho Discontinuity ??

Figure 11

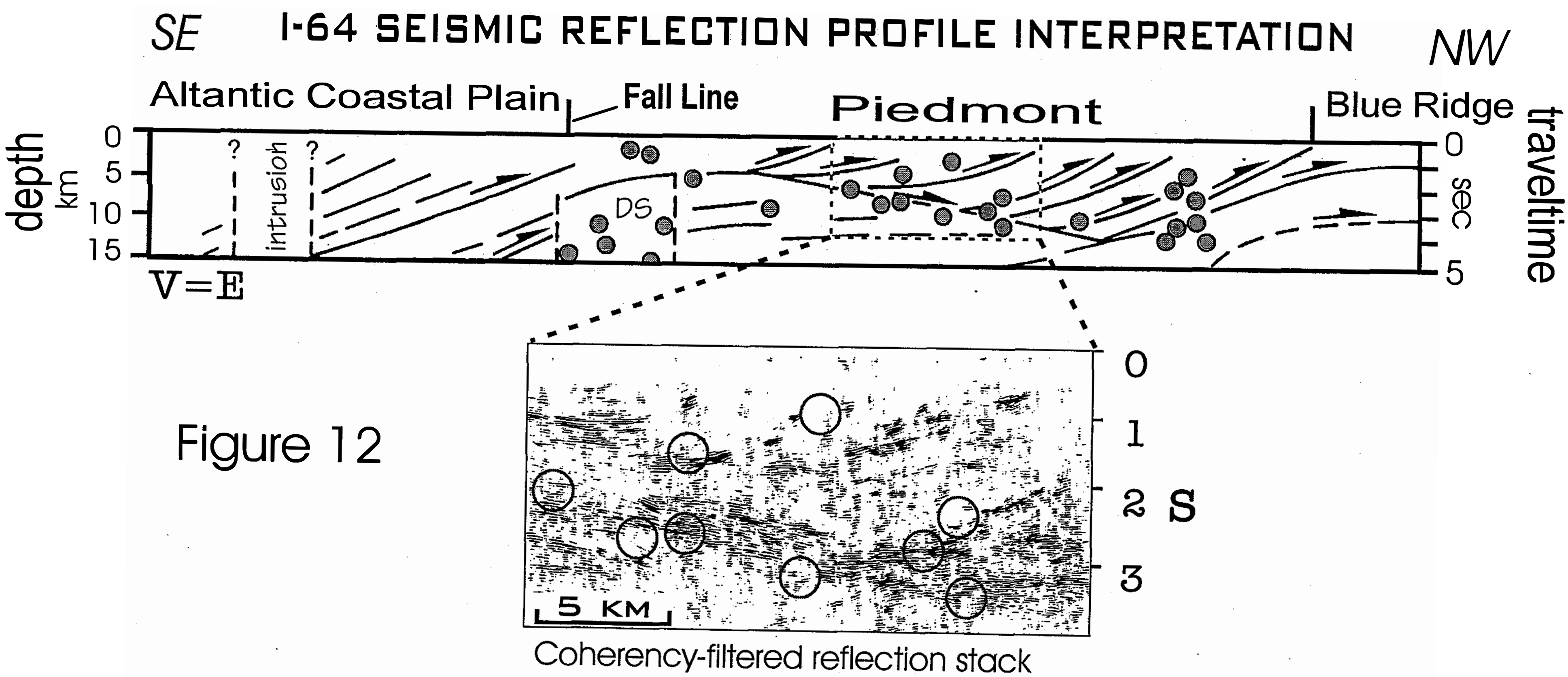
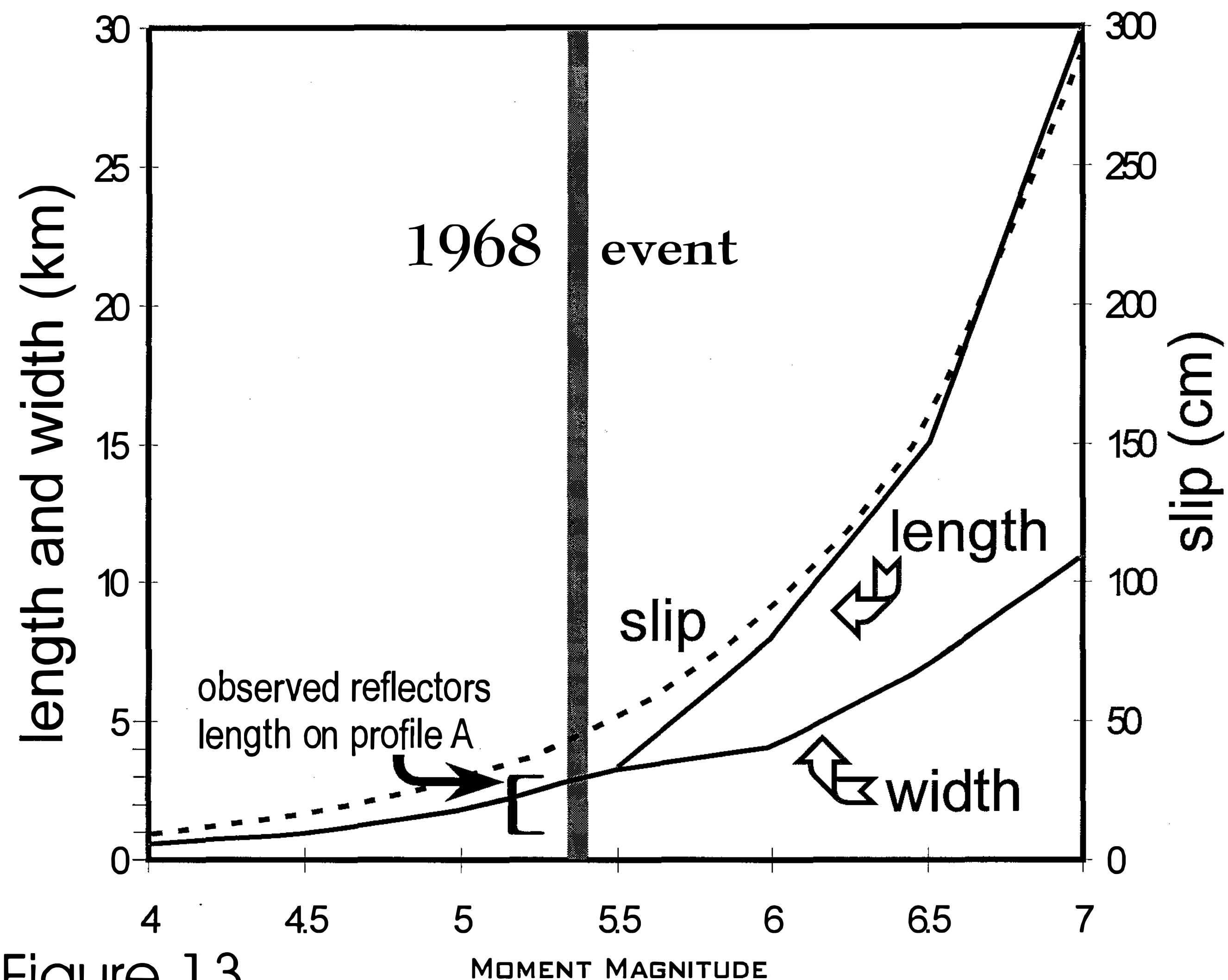

SE
I-64 SEISMIC REFLECTION PROFILE INTERPRETATION
NW
Altantic Coastal Plain
Fall Line
Piedmont
Blue Ridge
depth
km
0
5
10
15
V=E
?
intrusion
?
DS
traveltime
sec
0
5
0
1
2
3
S
5 KM
Coherency-filtered reflection stack

Figure 12



length and width (km)
slip (cm)
30
25
20
15
10
5
0
300
250
200
150
100
50
0
4
4.5
5
5.5
6
6.5
7
Moment Magnitude
1968
event
slip
length
width
observed reflectors
length on profile A

Figure 13

Table 1. Instrumentally Recorded Earthquakes of the "Wabash Valley Seismic Zone" $m_{bLg} \geq 3.0$

DATE (Yr.Mo.Dy)	DEPTH (km)	MAGNITUDE (m_{bLg})
1987.06.10*	10 ± 1	5.2
1980.03.13	20.3 ± 1.8	3.0
1978.12.05	23.4 ± 2.1	3.5
1978.06.02	20.4 ± 3.4	3.2
1974.04.03	13.5 ± 4.4	4.7
1971.02.12	15.0 ± 5.5	3.1
1968.11.09	21.2 ± 5.4	5.5
1962.06.27	6.8 ± 6.1	3.9
1958.11.08	4.9 ± 14.1	4.4

Data are from *Gordon* [1988] and *Langer and Bollinger* [1991] except for * from *Taylor et al.* [1989]. See Figure 2 for location.