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Deep seismic reflectivity beneath an intracratonic basin: Insights into the behavior of the uppermost mantle beneath the Illinois basin

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Abstract

Reflectivity images of the lower crust and uppermost mantle beneath the Paleozoic Illinois basin have been derived from reprocessing of several hundred kilometers of industry seismic reflection data using extended vibroseis recorrelation. The recorrelation was based on extending an originally 4-s correlated record, acquired with a 16-s sweep, from 14 to 126 Hz, to the absolute limit of the full 20 s (∼70 km) listening traveltime. Sub-Moho reflections are recorded to 18 s two-way traveltime (unmigrated) and are observed on intersecting profiles apparently dipping to the southwest and striking northwest–southeast. Occasional Moho reflections are also observed across the profiles (∼12 s or ∼38 km) while reflectivity in the lower crust is generally marked by intermittent horizontal packages and short, gently dipping reflections and diffraction segments. The presence of newly observed mantle reflectivity beneath the Illinois basin indicates significant uppermost mantle heterogeneity, relative to other parts of the USA studied using reflection methods. The mantle reflectivity effectively defines an area of anomalous mantle that rests beneath the depocenter of the early Paleozoic Illinois basin, which is itself superimposed over a deeper Proterozoic "basinal" depocenter. Filtering and inversion of geopotential field data reveal that this anomalous mantle also partially correlates with a positive density anomaly in the upper mantle. These correlations suggest that the anomalous mantle zone exerted an influence on the early Paleozoic subsidence of the basin, perhaps as a buried load due to eclogitization of former lower crust. The relatively isolated occurrence of sub-Moho reflections beneath the basin makes it difficult to uniquely infer their origin. However, available geologic and geophysical constraints, especially from geochemical and geochronological studies of drilled and exposed basement rocks, limit the possibilities to: (1) remnants or "scars" of sub-crustal processes associated with lithospheric extension or delamination related to the melting of the Proterozoic crust that led to the emplacement of the granite–rhyolite province that underlies much of USA Midcontinent; or (2) deformation caused by plate subduction associated with the hypothetical accretion of a juvenile island arc to the pre-1.6 Ga southern margin of the Laurentian continent.

Keywords: Proterozoic; Seismic reflection; Mantle; Plate tectonics

1. Introduction

As observed from over a quarter century of deep seismic reflection profiling of the continents, Earth's crust is highly structured in terms of physical properties contrasts. On the other hand, the uppermost sub-continental mantle is usually devoid of similar reflectivity contrasts (Steer et al., 1998). Remarkable exceptions, however, have been well documented beneath convergent orogens within the British Caledonides (McGeary and Warner, 1985; Snyder and Flack, 1990; McBride et al., 1995; Warner et al., 1996; Snyder et al., 1997), the Baltic Shield (BABEL Working Group, 1991), the southern Uralide orogen (Knapp et al., 1996), the northwestern Canadian Shield (Wopmay orogen and Slave Province) (Cook et al., 1998, 1999), as well as beneath contemporary plate

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boundaries (Melhuish et al., 2004). Much of the deep seismic work where mantle structures have been imaged has been across existing and ancient plate convergent boundaries (e.g. subduction zones). On the other hand, mantle reflectivity has only rarely been observed beneath continental interiors.

The purpose of this study is to present the results of reprocessing of industry reflection profiles from the Illinois basin, integrated with other geological and geophysical data, that reveal some of the first clear dipping sub-Moho reflections in the USA. Our study provides a rare opportunity to study signatures of ancient mantle processes in the context of a continental interior. Understanding the development of this reflectivity will provide insight into upper mantle processes in a poorly known area of Precambrian lithosphere beneath a presently stable craton. We also suggest a mechanism, based on the presence of anomalous mantle, that may have contributed to the subsequent early Paleozoic subsidence of the Illinois basin.

2. Regional setting

2.1. Geology

The Illinois basin (Fig. 1a) is an oval depression covering an area of approximately 285,000 km^2 in parts of Illinois, Indiana, and Kentucky (Kolata and Nelson, 1997). It is one of several large cratonic basins that developed on Precambrian crust of North America (Leighton and Kolata, 1991) and contains about 500,000 km^3 of primarily Cambrian through Pennsylvanian sedimentary rocks having a known maximum thickness of about 7600 m (Buschbach and Kolata, 1990; Goetz et al., 1992). The evolution of the basin has been influenced by several tectonic episodes, beginning with late Precambrian–Cambrian subsidence in east-central Illinois and east-central Indiana and failed rifting (Reelfoot rift and Rough Creek graben) in the southernmost part of the basin (Fig. 1a) (Kolata and Nelson, 1997; McBride et al., 2003). Between Late Cambrian and Early Permian time, the basin experienced widespread subsidence, developing into a broad southwest-plunging trough that extended to the cratonic margin (Kolata, 1991). The basin began to assume its present oval shape in the late Paleozoic with the rising of the Pascola arch (Fig. 1a) until the Reelfoot rift once again began to subside in the Late Cretaceous, ultimately forming the Mississippi embayment of the Gulf Coastal Plain (Schwalb, 1969).

The basin overlies an extensive granite–rhyolite basement commonly referred to as the eastern granite–rhyolite province (Fig. 1a), part of a large igneous province extending from northern Mexico to eastern Québec (Lidiak, 1996; Karlstrom et al., 1999). This province has been described either as a thin upper crustal layer or as a composite of isolated igneous intrusions. The rocks have been interpreted as anorogenic based on geochemical analyses, the lack of metamorphism commonly associated with convergent plate boundaries, and the apparent absence of deformation (Bickford et al., 1986). The lack of basement rocks with calc-alkaline chemistry (Shuster, 2001) further suggests an anorogenic environment. Bickford et al. (1986) suggest that the granites and rhyolites are underlain by crust produced by anatectic melting of the southeastward continuation of the older Proterozoic Central Plains Orogen (Fig. 1a), while Van Schmus et al. (1996) suggest that the deep crust was created from a parent magma generated from a mantle source just slightly older than the granites and rhyolites themselves. Van Schmus et al. (1996) proposed that multiple juvenile terranes were accreted from the southeast onto an older Paleoproterozoic Laurentian continental margin in order to develop this deeper crust. The locus for this accretion has been defined by a line (Fig. 1a) striking northeast from northwestern Texas to southeastern Michigan based on Sm–Nd studies. This line is interpreted to mark a rifted or foreland continental margin (Van Schmus et al., 1996). A common element of several of the proposed theories for the development of this igneous province is that extension of the lithosphere and heating of the crust are required in order to produce the high-silica granite melts in the uppermost crust (e.g. Bickford et al., 1986). In such cases, the province could be a result of the intrusion/extrusion of material following decompression melting in the lithosphere associated with rifting and extension. Schneider et al. (2004) have proposed that, in general, the amalgamation of the Laurentian continent along its southern Archean cratonic boundary during the Proterozoic involved northwest-directed convergence and subduction, which facilitated the southward growth of the USA Midcontinent.

2.2. Geophysics

Prominent “layered” reflectivity in the upper crust (∼1.5–4.0 s traveltime, ∼12 km depth) has been documented from deep seismic reflection profiles across the Illinois basin (“Centralia sequence”; Pratt et al., 1992; Drahovzal, 1997; Potter et al., 1997; McBride and Kolata, 1999; McBride et al., 2003). Pratt et al. (1992) and Lidiak (1996) have described the layered reflectivity as a hypothetical Proterozoic sedimentary basin or tabular mafic igneous bodies associated with either granitic basement or Proterozoic sedimentary

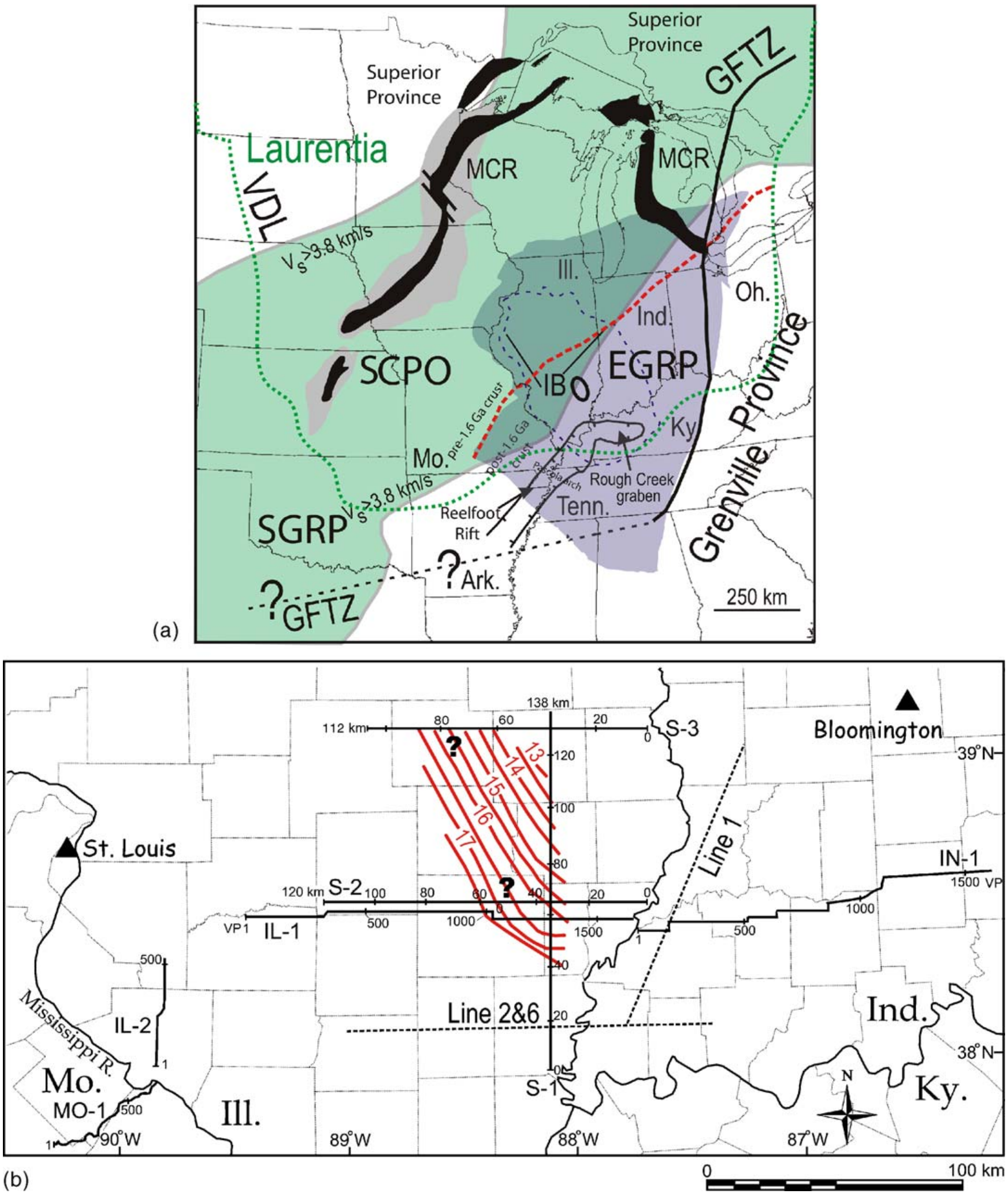


Fig. 1. (a) Index map of the study area showing the primary geologic basement and tectonic boundaries of the central USA. The outline of the Illinois basin (IB) is shown. The oval represents the mantle reflection area ((b) and Fig. 17). The dark shaded region delimits the eastern granite–rhyolite province (EGRP), while the black and shaded area represents the Midcontinent rift system (MCR). The thick northeast–southwest oriented dashed line indicates the inferred southern limit of pre-1.6 Ga crust, as defined by Sm–Nd isotope model ages from Van Schmus et al. (1996). GFTZ indicates the Grenville Front tectonic zone and SCPO is the southern Central Plains orogen. The short-dashed line represents the interpreted margin of the Laurentian continent based on elevated seismic velocity for the mantle at a depth of 140 km from Van der Lee (2001) (VDL). Light shading denotes area of crystalline crust with shear wave velocities greater than 3.8 km/s (Chulick and Mooney, 2002). See Van Schmus et al. (1996) and Lidiak (1996) for discussion of the ages of the various basement provinces. (b) Location map of deep seismic reflection (solid lines) and refraction (dashed lines) profiles referred to in this study. Lines S-1, S-2, and S-3 have been fully reprocessed for this study. COCORP profiles IL-1, IL-2, and IN-1 have been post-stacked reprocessed. Refraction profiles are from Braile et al. (1981) and Braile (1989). Labeled triangles refer to seismometer stations where receiver functions were computed by Akinci et al. (1999) for the area shown. Isotraveltime contours are superimposed for the mantle reflection (unmigrated) as shown, e.g. in Fig. 11b. Dashed faint lines indicate county boundaries.

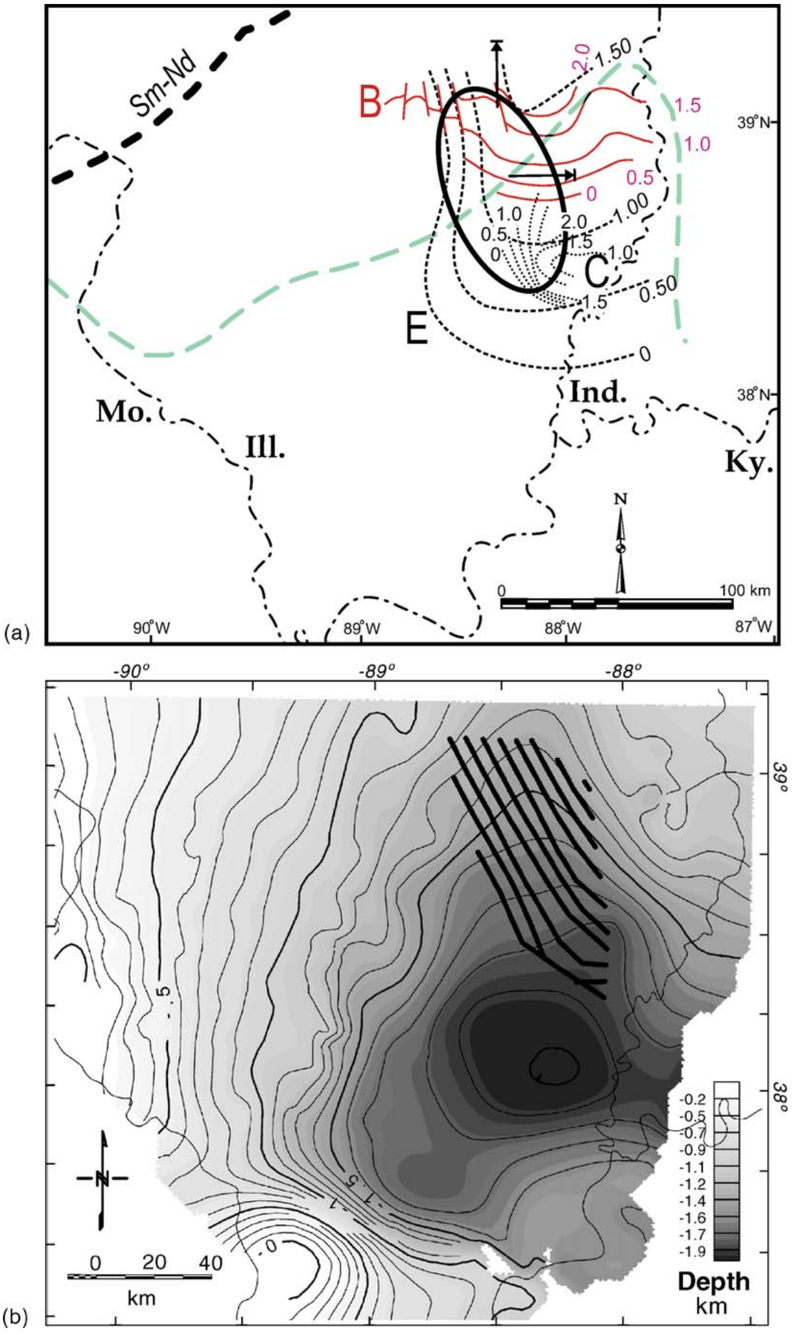


Fig. 2. (a) Isotraveltime structural contour maps of Precambrian surfaces based on reprocessed and COCORP deep seismic reflection profiles (Fig. 1b) from McBride et al. (2003). Long dashed line is traveltime isopach map for the interval between the base of the Mt. Simon Sandstone and the base of the “Enterprise” subsequence (“E” in Fig. 6a) (McBride and Kolata, 1999). Traveltime isopach maps are also shown for the northern and southern sub-Centralia sequences (solid and dashed black lines, respectively) (“B” and “C”, respectively, in Fig. 6a). See McBride et al. (2003) for more information. Contour interval is 500 ms. Sm–Nd marks the boundary of the pre-1.6 Ga and post-1.6 Ga crust defined by Nd isotope data (Van Schmus et al., 1996) (Fig. 1a). The light dashed line cutting across most of the map represents the northern limit locally of anomalous high-density mantle as computed from inversion of Bouguer gravity data (Fig. 14a). Black oval represents approximate area of mantle reflection observed in this study (Fig. 1b). In this and subsequent figures showing the position of the mantle reflection, it should be noted that the unmigrated position is shown. The migrated position, corrected for profile obliquity, would position the reflector pattern to the east and north as shown by two arrows. See text for details. (b) Structure map of top of Middle Ordovician Trenton Formation (source is Illinois State Geological Survey) shown as contour map (interval is 100 m) and gridded values. Also shown is position of mantle reflection.

strata. Maps of the distribution of the layered reflectivity in the uppermost crust (e.g. Fig. 2) were first produced by McBride and Kolata (1999) and McBride et al. (2003), based on previously available and reprocessed industry seismic reflection data from the central part of the basin. On the basis of the geometry and internal structure of the layered reflectivity, they suggest a collapsed caldera complex or late Proterozoic rift basin for the local origin of the granite–rhyolite province underlying the central Illinois basin.

Although other geophysical information on the Precambrian crust below the Illinois basin is somewhat limited, sufficient data exist to characterize the velocity structure of the crust and uppermost mantle, as well as the regional crustal thickness for the study area (e.g. see compilations by Braile (1989), Heigold (1991), and Chulick and Mooney (2002)). Regional seismic refraction data have been used to obtain velocity-depth models of the crust (Braile et al., 1981; Ginzburg et al., 1983; Braile, 1989; Catchings, 1999), which can be used for converting reflection traveltimes to depth (Fig. 3). The results of two seismic refraction profiles (Fig. 1b) over the Illinois basin have been reported by Braile et al. (1981), which indicate almost identical Moho depths and bulk velocity structures (and thus traveltime to the Moho discontinuity) (Fig. 3). These results have been incorporated into a contour map of crustal thickness for the central USA by Braile (1989). From an east–west refraction profile across the southern margin of the study area (Fig. 1b), Braile et al. (1981) indicated a generalized upper Precambrian crustal compressional wave velocity of 6.13 km/s and a middle and lower crustal velocity of 6.74 km/s (Fig. 3), which are broadly comparable to values derived for the upper and middle crust from refraction profiles for the northern Mississippi embayment to the south (6.20 and 6.60 km/s for the upper and middle crust, respectively) (Ginzburg et al., 1983). Braile et al. (1981) also determined a crustal thickness of about 37.5 km (Fig. 3), which is consistent with more recent compilations of crustal thickness for the study area that show a value between 35 and 40 km (Braile, 1989; Mooney and Braile, 1989; Chulick and Mooney, 2002).

Based on a comprehensive compilation of seismic velocity information, Chulick and Mooney (2002) show a wide belt of higher than average shear-wave velocity (>3.8 km/s) for “consolidated (crystalline)” crust that trends in a northeast direction from southwest Texas to northeast of the Great Lakes (Fig. 1a). Chulick and Mooney (2002) interpret this belt of higher velocity to represent a core of cold and older Precambrian cratonic crust. The southeastern boundary of the belt trends diagonally across southern Illinois, sub-parallel to and just south of the Sm–Nd boundary (Fig. 1a).

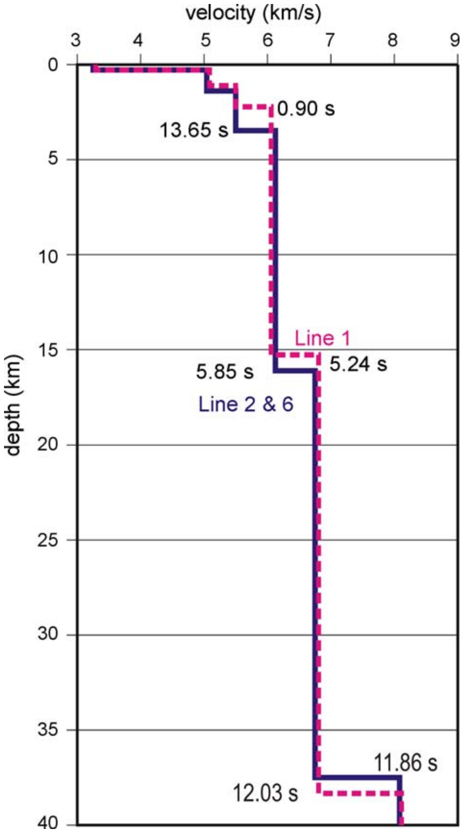


Fig. 3. Two 1D velocity-depth models of the crust and upper mantle for the study area from Braile et al. (1981) (see also Braile, 1989). Small numbers are the equivalent two-way traveltimes corresponding to the major boundaries in seismic velocity. See Fig. 1b for locations of “Line 1” and “Lines 2 and 6”.

A seismic refraction profile acquired over the southwestern flank of the Illinois basin stretching from Memphis, Tennessee northward to just east of St. Louis, Missouri (Fig. 1b) provides a model where crustal velocities and crustal thickness are greater than for our study area (about 45 km near St. Louis; Catchings, 1999); however, as shown by the compilations by Braile (1989) and Chulick and Mooney (2002), a significant increase in crustal thickness is expected beneath the western flank of the Illinois basin toward the Ozark dome ~80 km northwest of the Pascola arch (Fig. 1a). We also note that Catchings’s (1999) north–south velocity model shows a flat mantle refractor just above 60 km depth.

Converting Braile et al.’s (1981) one-dimensional velocity models from depth to time gives traveltimes to the Moho of ~11.9 s (for 37.5 km from their “Line 2 and 6”) and ~12.0 s (for 38.4 km from their “Line 1”)

(Fig. 3). The seismic velocity for upper mantle within the area is given as 8.1 km/s.

The results from seismic refraction modeling for the Illinois basin agree generally with results from teleseismic receiver analysis, which give Moho depths of about 40 km (Akinci et al., 1999) (Fig. 1b). Although previous dedicated deep seismic reflection profiles have been acquired and processed to 20 s over the Illinois basin and adjacent areas by the Consortium for Continental Reflection Profiling (COCORP), coherent reflections beyond about 4 s, including lower crustal or Moho reflections, were not commonly observed, and no mantle reflections were described (Pratt et al., 1989).

2.3. Methodology

Reprocessing of several hundred kilometers of industry seismic reflection data using extended vibroseis correlation was performed. The original industry profiles were acquired along three regional lines (Fig. 1b, S-1, S-2 and S-3, totaling 386 km length), which intersected COCORP Illinois Line 1 (Pratt et al., 1989, 1992) and other proprietary industry profiles (McBride and Kolata, 1999). The profiles were surveyed in the mid-1980s and used a source interval of 165 ft (∼50 m), recorded over a 20,460 ft (∼6.23 km) geophone array with 120 channels (24 geophones/channel).

The initial processing step was to extend the original 4 s correlated record to the absolute limit of the full 20 s listening time using the "self-truncating" method of vibroseis recorrelation (Okaya and Jarchow, 1989). This method uses the full-frequency bandwidth for the duration of the original correlated data, beyond which the correlation proceeds with a linearly decreasing bandwidth due to loss of the highest frequencies followed by gradually lower frequency components (Fig. 4). The correlation operator is allowed to truncate automatically using as much of the operator length as possible for reflections after the 4-s full-bandwidth record length. This approach is practical for basement targets because higher frequencies tend to be progressively attenuated with increasing traveltime. This means that the loss of high-frequency signal with extended correlation is apt to follow the loss due to attenuation. The very long recorrelation time in our case was viable due to the unusually long listening time for the record, the long source signal (sweep duration = 16 s), and its broad, linear increase of frequency with time from 14 to 126 Hz (Fig. 4). Thus, the frequency content of the recorrelated data for expected lower crust-uppermost mantle traveltimes (e.g. 10–16 s; Fig. 5a) mimicked that for the previously surveyed COCORP profiles (Pratt et al., 1989). The unusual combination of broad frequency bandwidth and long sweep length and listening time provides frequency components suitable for simultaneously imaging reflectors from shallow sedimentary rocks, the deep crust, and the uppermost mantle (Fig. 5a).

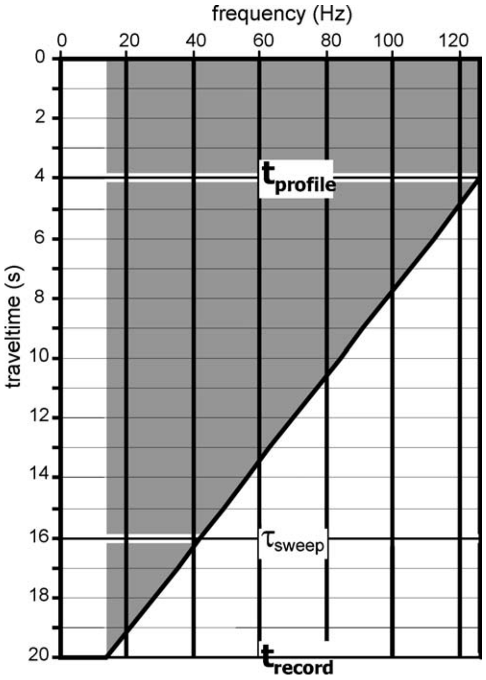


Fig. 4. Graph illustrating decrease in frequency bandwidth with traveltime for the parameters used in the extended recorrelation for this study. The original correlated data length (t_{profile}) was 4 s, the vibroseis sweep length (τ_{sweep}) was 16 s, and the total listening time (t_{record}) was 20 s. See text and Okaya and Jarchow (1989) for more explanation.

The post-correlation reprocessing was designed to enhance the low-frequency portion of the signal returning from the lower crust and upper mantle. The critical processing steps included: (1) application of a 8–12.5–40–50 Hz Ormsby frequency filter; (2) subsample to 8 ms; (3) test migrations over a range of velocity functions expressed as percent of the 2D interval velocity (0, 70–100%); (4) application of a post-stack low-apparent velocity rejection filter using a limited aperture tau-p (zero offset traveltime intercept-slowness) transform (e.g. Yilmaz, 1987); (5) application of residual static corrections. Several migration trials using a phase-shift method were performed to avoid overmigration artifacts and to determine which apparently linear events might be diffractions. Both migrated and unmigrated sections were examined for our study. Selected portions of the records are shown with a post-stack coherency filter as developed by Lithoprobe at the University of Calgary (e.g. van der Velden and Cook, 2005). We present the results of the reprocessing as interpre-

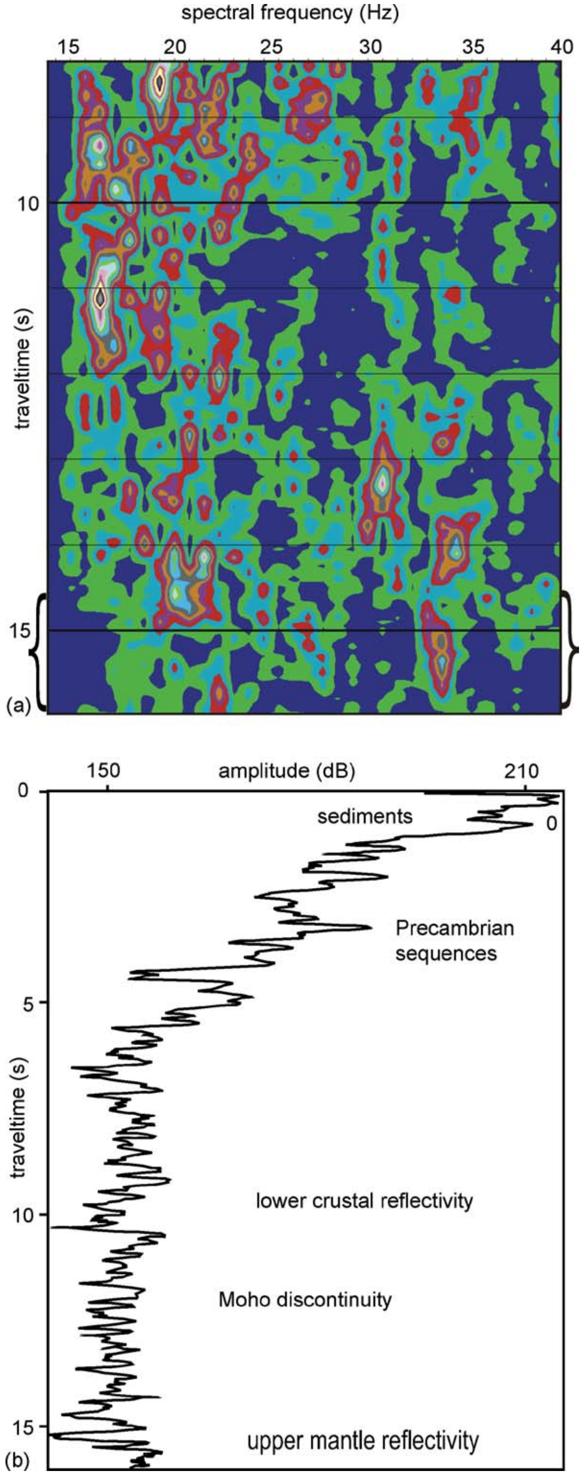


Fig. 5. Frequency and "true" amplitude analyses for the higher quality portion of line S-1 over area of prominent mantle reflection ("b", Fig. 6a), below which theoretical frequency content drops below 40 Hz (Fig. 4). (a) Frequency spectra over onset of mantle reflectivity (shown by brackets) indicating persistence of usable frequency content into the upper mantle. For an observed frequency peak at 33 Hz and an assumed velocity of 8.1 km/s, the Rayleigh criterion yields a vertical resolution for mantle reflectivity of about 60 m. (b) Graph illustrating natural amplitude decay (with no gain or spherical divergence correction) with traveltime from average traces over area of the prominent mantle reflection on N-S section, S-1. Continued small amplitude decay to bottom of record implies continued signal penetration.

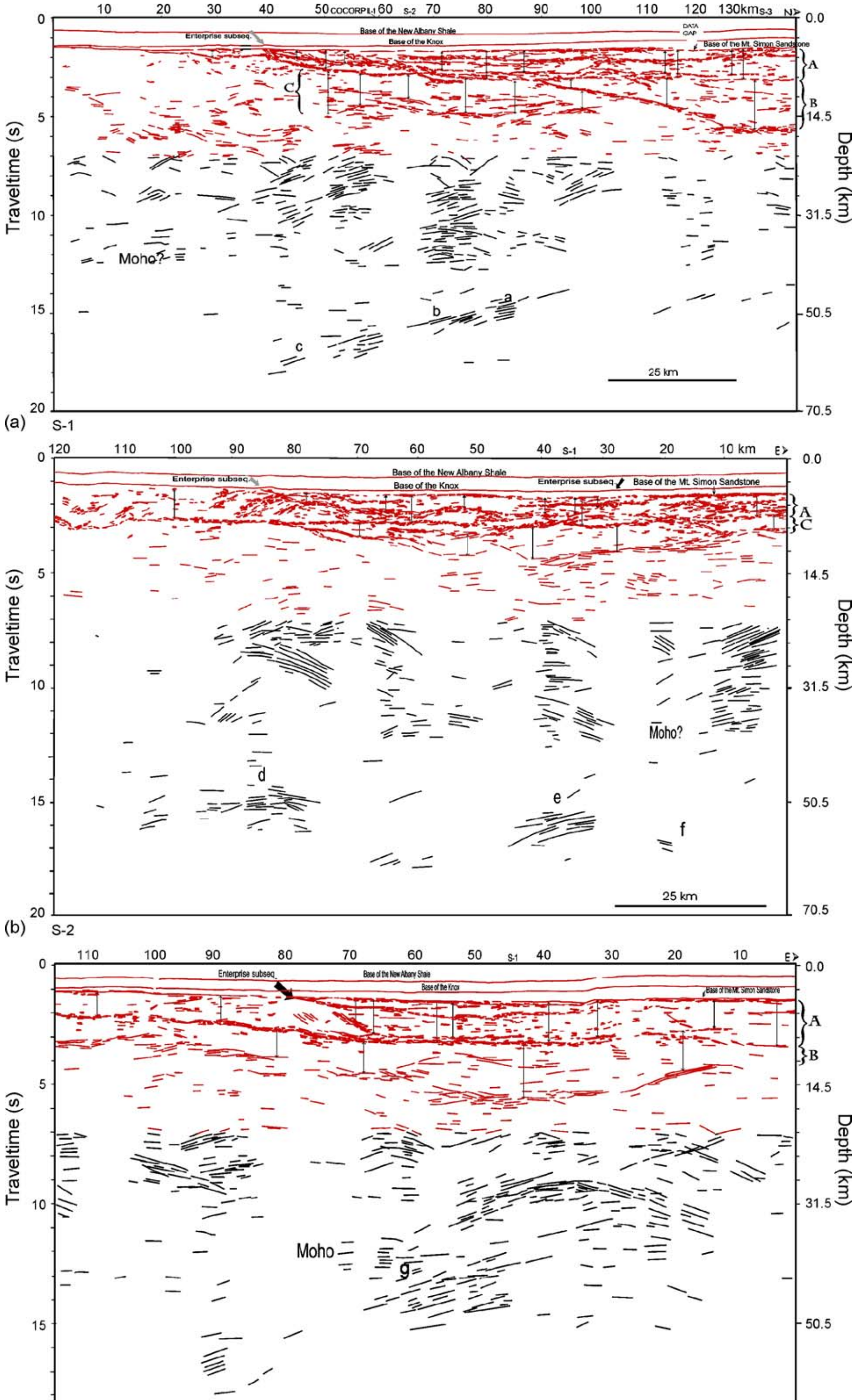
tive line drawings of the previously processed migrated records from 0 to 7 s combined with the results of the new deep recorrelation processing from 7 to 20 s from unmigrated stacked sections (Fig. 6). The deeper results are presented as unmigrated in order to avoid possible over-migration artifacts and to enable the direct recognition of diffracted events. Those parts of the deep records that are critical to our interpretation are shown as excerpts of the migrated form of the data. In order to account for the possible obliquity of the profiles to dipping sub-Moho reflections, we have employed a simple straight-ray migration approximation following the approach of Chun and Jacewitz (1981) and Li and Eaton (2005). This is usually not possible with common mid-point reflection surveys showing mantle reflections due to lack of 3D coverage. Our study is one the few for which such coverage is available. The description and interpretation of upper crustal reflector structure are presented elsewhere (McBride and Kolata, 1999; McBride et al., 2003).

3. Results and interpretation

Our observations from the reprocessing results are grouped as: (a) upper crustal reflectivity (0–7 s); (b) lower crustal and Moho discontinuity reflectivity (7–12 s); (c) uppermost mantle reflectivity (12–20 s). Fig. 6 shows line drawings of the reprocessed seismic profiles S-1, S-2 and S-3 from 0 to 20 s. In our 2D mapping of reflections, we incorporated the COCORP profiles. The reprocessed profiles show intermittent but clear images of lower crustal reflections and diffractions, the Moho, and sub-Moho and upper mantle reflections. The quality of the images exceeds that of the COCORP profiles.

3.1. Upper crustal reflectivity

Distinct nearly horizontal reflections define the sedimentary units corresponding to the Paleozoic Illinois basin (Heigold, 1991; Pratt et al., 1992; McBride and Kolata, 1999). McBride et al. (2003) provided a detailed description of the upper crustal reflectivity of interpreted Proterozoic sequences ("Centralia sequence") using 10 s (∼30 km) record sections. In their study, they noted that beneath the Paleozoic strata of the Illinois basin, Pro-


(a)
S-1
10 20 30 40 50 COCORP IL-1 60 S-2 70 80 90 100 110 120 130km S-3 N
Enterprise subseq.
Base of the New Albany Shale
Base of the Knox
DATA GAP
Base of the Mt. Simon Sandstone
A
B
C
Moho?
a
b
c
25 km
Traveltime (s)
Depth (km)
0 5 10 15 20
0.0 14.5 31.5 50.5 70.5
(b)
S-2
120 110 100 90 80 70 60 50 40 S-1 30 20 10 km E
Enterprise subseq.
Base of the New Albany Shale
Base of the Knox
Enterprise subseq.
Base of the Mt. Simon Sandstone
A
C
Moho?
d
e
f
25 km
Traveltime (s)
Depth (km)
0 5 10 15 20
0.0 14.5 31.5 50.5 70.5
(c)
S-3
110 100 90 80 70 60 50 S-1 40 30 20 10 E
Enterprise subseq.
Base of the New Albany Shale
Base of the Knox
Base of the Mt. Simon Sandstone
A
B
Moho
g
25 km
Traveltime (s)
Depth (km)
0 5 10 15 20
0.0 14.5 31.5 50.5 70.5

terozoic reflectivity is complex and highly structured and appears to be embedded in or part of the eastern granite–rhyolite province. They described the overall Proterozoic structure in the ∼1.5 to 6–7 s interval as dish- or wedge-shaped reflection packages bound by a narrow reflection band that is subhorizontal to moderately dipping (Fig. 6a and b). The geometry of reflections in some places suggests stratiform unconformity-bounded deposits that could be interpreted as seismic stratigraphic sequences of sedimentary and/or volcaniclastic layers (Fig. 2).

Pratt et al. (1992) originally described the "Centralia sequence" as a hypothetical Proterozoic sedimentary basin based on the Illinois and Indiana COCORP profiles (Fig. 1b). Based on a loose network of industry seismic profiles, McBride and Kolata (1999) and McBride et al. (2003) subdivided Precambrian reflectivity into three prominent sequences A, B, and C as shown in Fig. 6. The Enterprise subsequence is a distinct bowl-shaped succession of reflective units, possibly depositional, in the upper part of the Centralia sequence immediately beneath the Cambrian Mt. Simon Sandstone with distinct pinch-out boundaries (Fig. 6).

3.2. Lower crustal reflectivity and the Moho

The lower crust (7–12 s) is represented as intermittent horizontal reflection packages and short gently dipping reflections and diffractions (Fig. 6). As seen for other areas of the Midcontinent from deep reflection profiles (Brown et al., 1983; Serpa et al., 1984), large areas of diffractions and associated reflection segments dominate much of the section, such as appears in the deep crust near the western end of S-2 (Figs. 6b and 7a). Upon migration, the diffractive zones collapse into discontinuous "pods" of segmented or dipping reflections (Figs. 7a and 8).

Perhaps the most notable feature of the lower crust is the rather abrupt cessation of reflectivity across the traveltime range of 11.5–12.5 s (Fig. 6). For example, a series of horizontal reflections appears between 11.3 and 11.6 s (∼37 km depth) on profile S-2 near the intersection of S-1 (Fig. 7b). The crustal section immediately above this level is marked by complex reflection geometries including dipping reflections that are truncated by the deeper horizontal reflections (see also Fig. 8). Below about 11.6 s, the section is remarkably blank except for deeper dipping events, discussed below. This division in reflectivity is also observed on the eastern end of the S-2 profile, where a gradual vertical cessation of reflectivity is observed at about the same traveltime (Fig. 7c). The lower crustal reflection pattern on S-1 (Fig. 8) matches that of S-2. On line S-1 prominent horizontal to sub-horizontal reflections appear at ∼11.5 s, especially beneath the middle of the profile (Fig. 6). These reflections also mark a division between complex lower crustal reflectivity and a greatly reduced reflectivity below (Fig. 8). Similarly, on profile S-3, limited intermittent horizontal reflections appear within the 11.5–12.5 s interval above deeper dipping reflections and diffractions (Figs. 6c and 9).

The arrival time, 11.5–12.5 s, for the boundary between a reflective and poorly reflective section corresponds to the Moho discontinuity as defined from modeling of local seismic refraction profiles and from receiver functions (Figs. 1b and 3) and from regional crustal thickness compilations as described above. We thus interpret this reflectivity boundary as the Moho, which corresponds to depths of 37–39 km (Fig. 3). The Moho is typically defined worldwide by the limit of lower crustal subhorizontal reflectivity (e.g. Klemperer et al., 1986; Prussen, 1991; BABEL Working Group, 1993; Cook, 2002). Although the Moho is also occasionally observable as a distinct horizontal reflector, it is more commonly defined by a cessation of crustal reflectivity that conforms well with refraction data modeling. Although the lower crust beneath the Illinois basin is reflective, a so-called "layered lower crust" as observed beneath some rifted provinces such as the North Sea and Basin and Range (e.g. Warner, 1990), is not observed. Amplitude decay curves computed from stacked common depth-point records from S-1 with no amplitude correction or deconvolution processing (e.g. Fig. 5b) typically show a strong decay to 6–7 s, followed by a sloping or nearly vertical curve to the bottom of the record; however, the decay is interrupted by a subtle change in slope and/or a localized amplitude peak around 11.5 s, which is consistent with the observed loss of reflectivity beyond about 11.5 s.

On a published line drawing interpretation of the COCORP deep seismic reflection profile Illinois-1 (Pratt

Fig. 6. Line drawings of three regional reprocessed seismic reflection profiles, S-1, S-2, and S-3 (a–c). On each profile, the first 7 s has been interpreted from the migrated form of the data (McBride et al., 2003) and the remaining 13 s is shown unmigrated (excerpts of critical areas are shown migrated in subsequent figures). Capital letters (A–C) refer to Proterozoic seismic stratigraphic sequences discussed in the text and shown in map view in Fig. 2. Vertical exaggeration is about 1:1 for a conversion velocity of 8 km/s. In this and subsequent figures, small case letters refer to reflection features discussed in the text. The seismic data for this figure and all other displays of the S profiles are provided by Seismic Exchange Inc.; in all cases, the interpretation is that of the authors.

et al., 1989), which orthogonally intersects S-1, a base of crustal reflectivity is not usually discernible, although Pratt et al. (1989) suggested a possible Moho arrival time of 15–16 s; however, this estimate conflicts with the results of local and regional seismic velocity models, as discussed above. Deeper portions of the Illinois-1 have not actually been published (except in an atlas available from Cornell University) or discussed directly in the literature. For this reason, we have applied a post-stack reprocessing of Illinois-1, equivalent to that for the industry data, in order to compare the two data sets (Fig. 10). Although the reprocessed industry data show greater signal penetration, the basic features of the profiles, where they intersect or are located near one another, are similar. Near the intersection of S-1 and Illinois-1, faint but recognizable reflections from the lower crust (~7–12 s) appear on the latter (Fig. 10) like those seen on S-1 with a lowermost reflection arriving at 11.5 s, which is close to the interpreted Moho reflection observed from S-1.

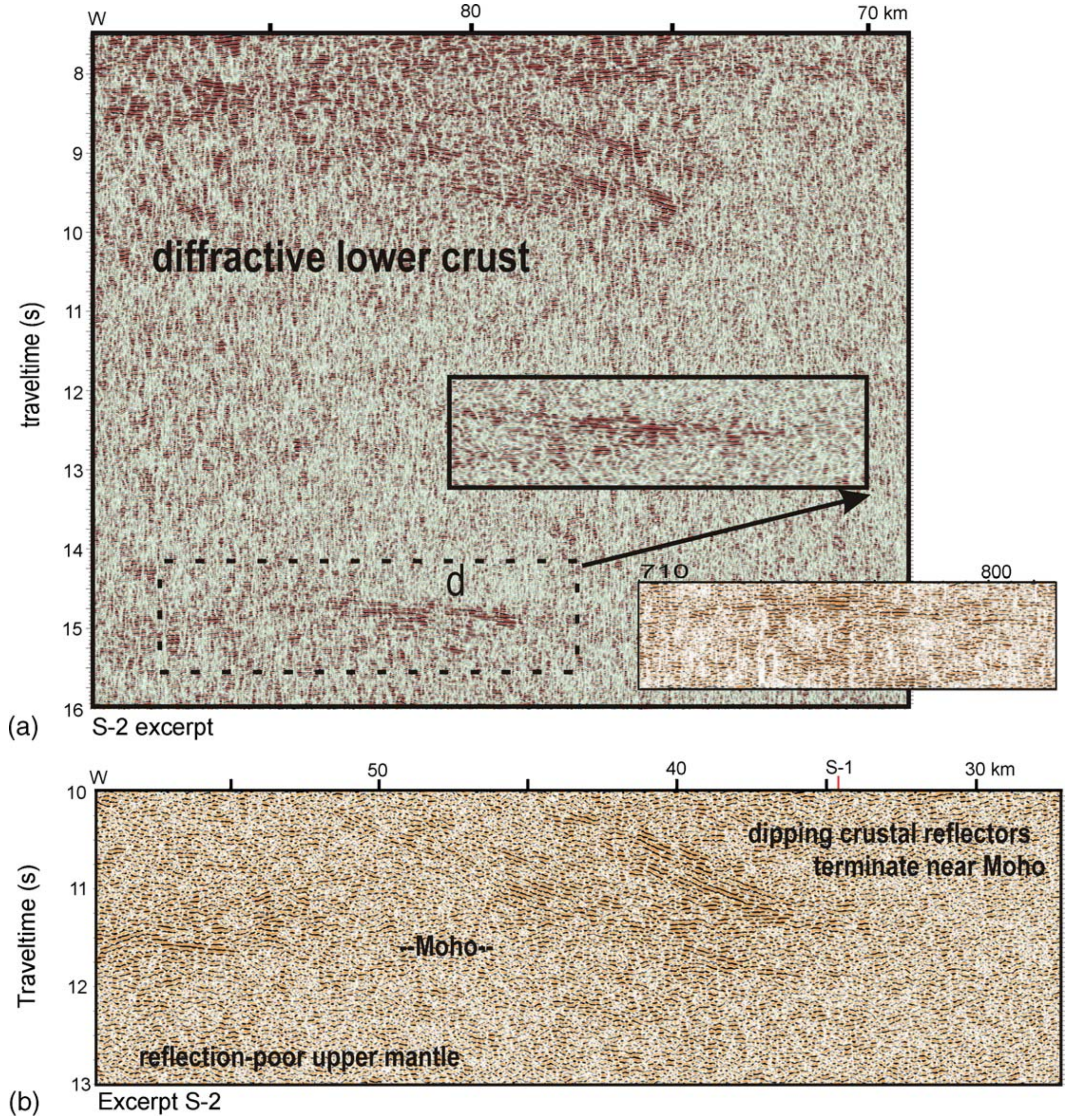


Fig. 7. (a) Excerpt section from profile S-2 illustrating mantle diffraction/reflection “d” (unmigrated). Inset rectangle at upper right shows migrated section for the mantle event. A very similar event arrives at 14.4 s on nearby profile IL-1 centered beneath station 760 (Fig. 1b) as shown in lower right inset (time scale is same as above inset). (b) Excerpt from migrated profile S-2, near the intersection with S-1, illustrating lower crust and Moho. (c) Eastern end of S-2, showing interpreted lower crustal and Moho reflectivity. For these and subsequent figures, the reader may refer to the line drawings (Fig. 6) and map (Fig. 1b) for geographical reference.

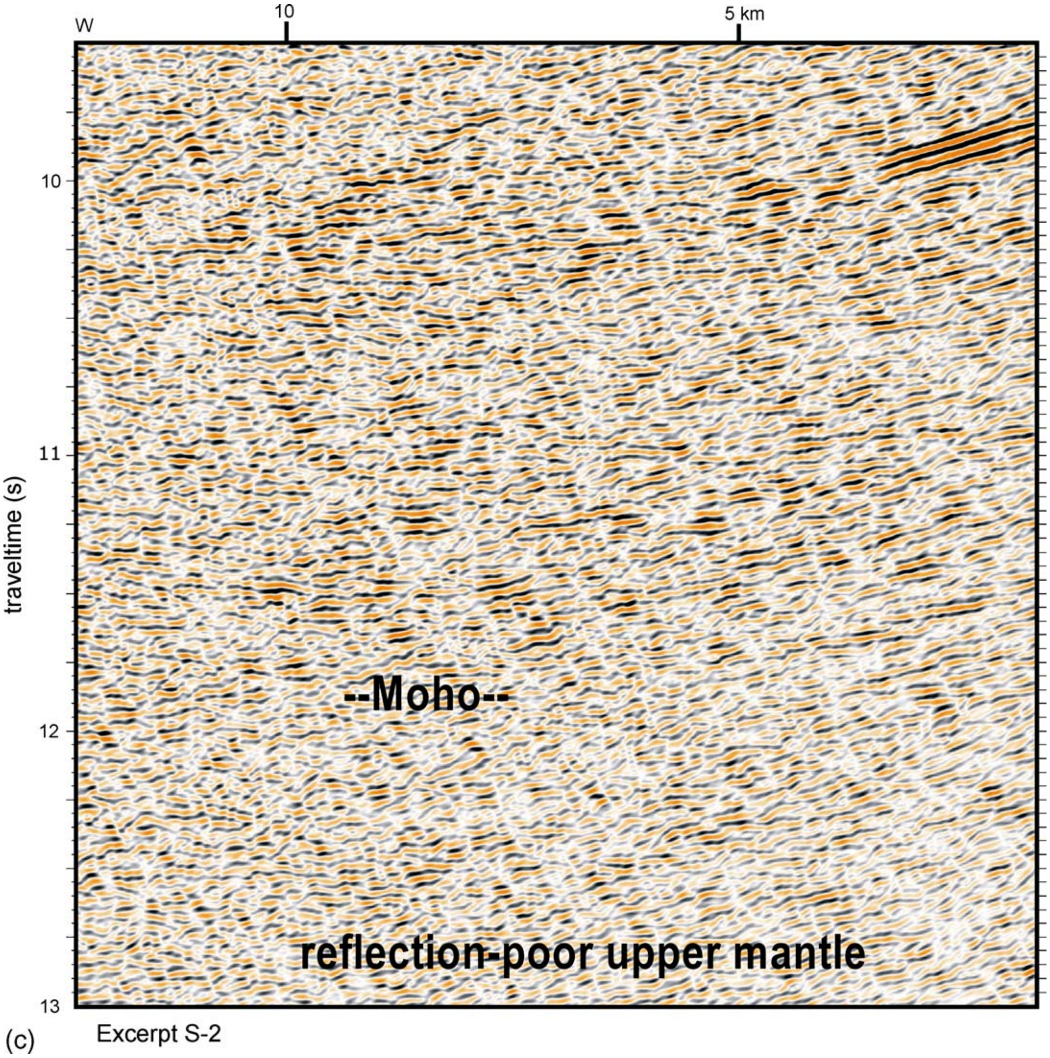


Fig. 7. (*Continued*).

3.3. Uppermost mantle reflectivity

Numerous reflections are observed beyond the Moho arrival time of 12 s, as depicted along the line drawing sections (Fig. 6). The correlation of unmigrated reflections across intersecting profiles enabled mapping of an apparent unmigrated surface arriving at mantle traveltimes, making the simplifying assumption that the arrivals are returning from a single surface. This not only corroborates our observations, but provides the first case of obtaining an approximate 3D position for a mantle reflection from common mid-point reflection profiles in the USA. Based on 2D mapping of the unmigrated reflections (Fig. 1b), a generalized dip azimuth of 240° is observed. We have also produced a smoothed contour map of the unmigrated mantle reflections, based on picking the first onset of mantle reflectivity on the records (Fig. 1b). Areas of less certainty on the contour map, for example where reflection continuity is projected between good-quality areas (e.g. Fig. 6c), are denoted as "?" (Fig. 1b).

Due to the close proximity in arrival time between some sub-Moho reflections and the Moho itself, we have examined mantle arrivals in unmigrated form and with various migration trials using different velocities (up to 8 km/s). Reflections arriving later than 12 s appear as discrete, isolated gently dipping events before and after migration, and do not move upward into the crust after seismic migration is applied on the 2D sections; however, due to the high likelihood that long-traveltime dipping reflections arrive from out of the plane of the section, we have attempted to account for the obliquity

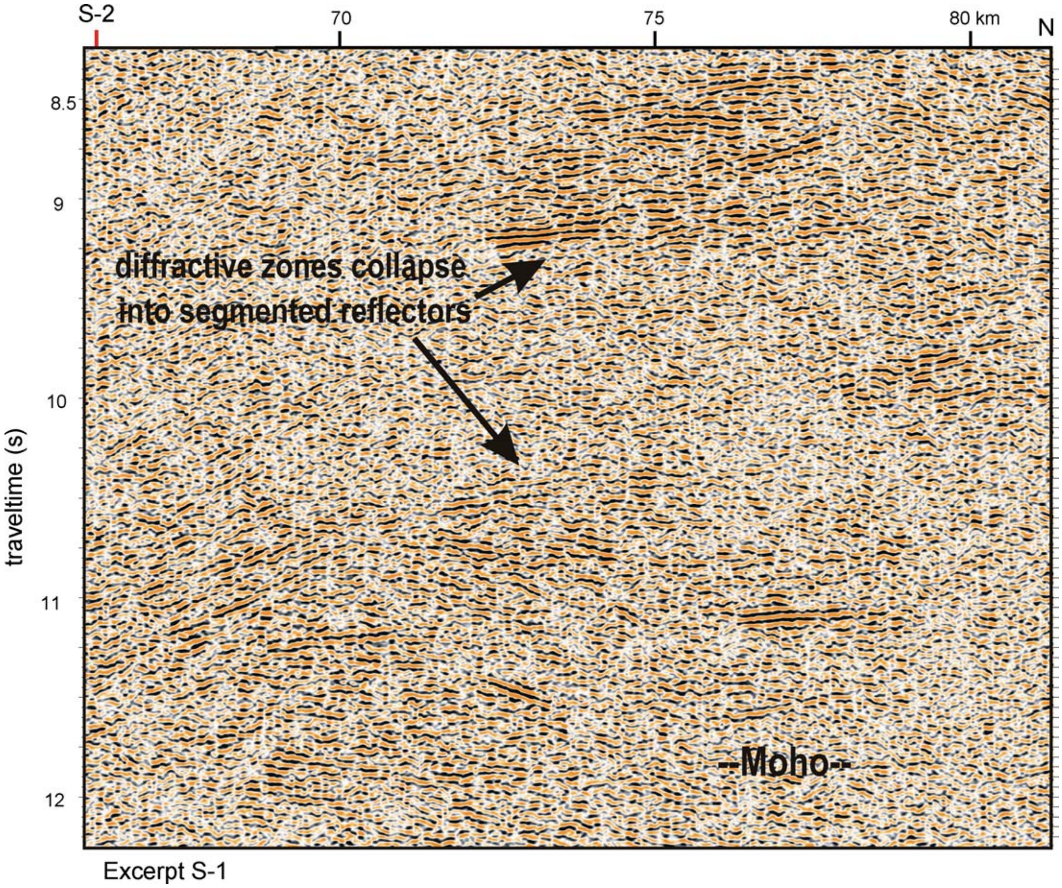


Fig. 8. Excerpt from migrated S-1 profile showing lower crustal and Moho reflectivity near the intersection with profile S-2.

of the sections relative to a dipping surface. Using a manual straight-ray migration approach (Chun and Jacewitz, 1981; Li and Eaton, 2005), we can provide some approximate constraints on how obliquity would influence the 3D position of the migrated reflectors. In order to approximate 3D position, we must first obtain a general dip azimuth of the mantle reflector or reflector "zone" as discussed above. The second required parameter is root-mean square (rms) velocity, which we derive from the layer velocities in the forward models of Braile et al. (1981). For example, for a traveltime of 15 s, the derived rms velocity is ~6.7 km/s (from their "Line 2 and 6"). Using these two parameters and the formulation for straight-ray migration (see Li and Eaton (2005) for review), the migrated traveltime on an oblique section is computed for an observed apparent slowness and traveltime of an unmigrated event. Inherent in using this simple approach are the assumptions that the reflectivity is simple enough to be approximated as a single dipping plane. Although this is clearly a severe simplification of what is likely to be complex structure involving a zone of deformation with complex surfaces, it does allow a better understanding of the source of the mantle traveltime reflections in a way that has usually not been applied or possible.

Sub-Moho reflections in some cases appear beneath zones of enhanced lower crustal reflectivity, within "columns" of higher signal–noise ratio caused perhaps by localized zones of greater signal penetration. This effect suggests that the actual length of post-12-s reflections could be longer than we have interpreted them (Fig. 6). The "column" effect is especially noticeable on line S-2 (70–75 km, Fig. 7a), where the lateral extent of lower crustal and mantle reflectivity is interrupted by a "column" of poor coherency (see also line S-1, 78–82 km, Fig. 11), implying a greater lateral extent than that shown. We note that this effect is also observed on the COCORP Illinois profiles, although with greater severity (Pratt et al., 1989) (e.g. Fig. 10). After the application of a coherency filter, reflections can in places be observed spanning what appeared as a gap before filtering (e.g. between "b" and "c" in Fig. 11b).

As seen from “true amplitude” decay curves, integrated for the region of the mantle reflectivity on line S-1 (Fig. 5b), amplitude levels for returning signal from the mantle are equivalent to those from the lower crust and Moho. Frequency spectra (Fig. 5a) show peak values of 21–34 Hz at 14–16 s at mantle traveltimes, which is within the expected frequency band based on the theoretical recorrelation bandwidth of 14 to ∼42 Hz at 16 s (Fig. 4). A 21–34 Hz signal would provide a favorable vertical resolution limit, using the Rayleigh criterion (i.e. the quarter-wavelength vertical resolution criterion), of 96–60 m for a mantle P-wave velocity (8.1 km/s).

On north–south profile line S-1 a prominent group of mantle reflections (“a”) arrives at 15.25 s (51 km depth) at 83 km, just north of line S-2 (Figs. 6a and 11). This reflection group has a minimum horizontal length

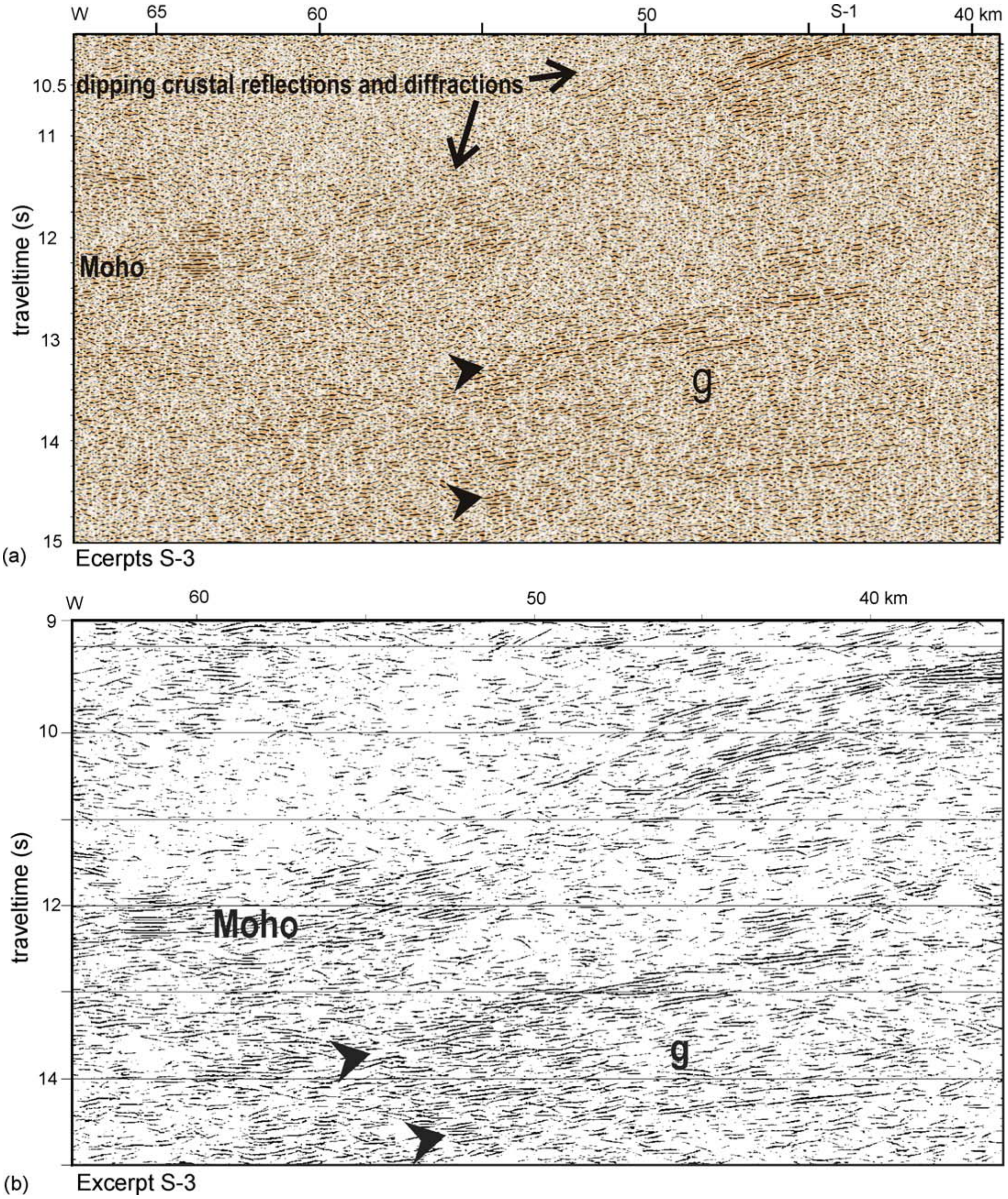


Fig. 9. (a) Excerpt from migrated profile S-3 illustrating Moho discontinuity and mantle reflection “g”. (b) As in (a), but with coherency filter added similar to the filters applied to Lithoprobe seismic data (e.g. Cook et al. (1999). (c) Excerpt from migrated profile S-3 showing interpreted down-dip (i.e. further west) portion of dipping mantle reflections shown in (a and b). Processing is the same as for (b).

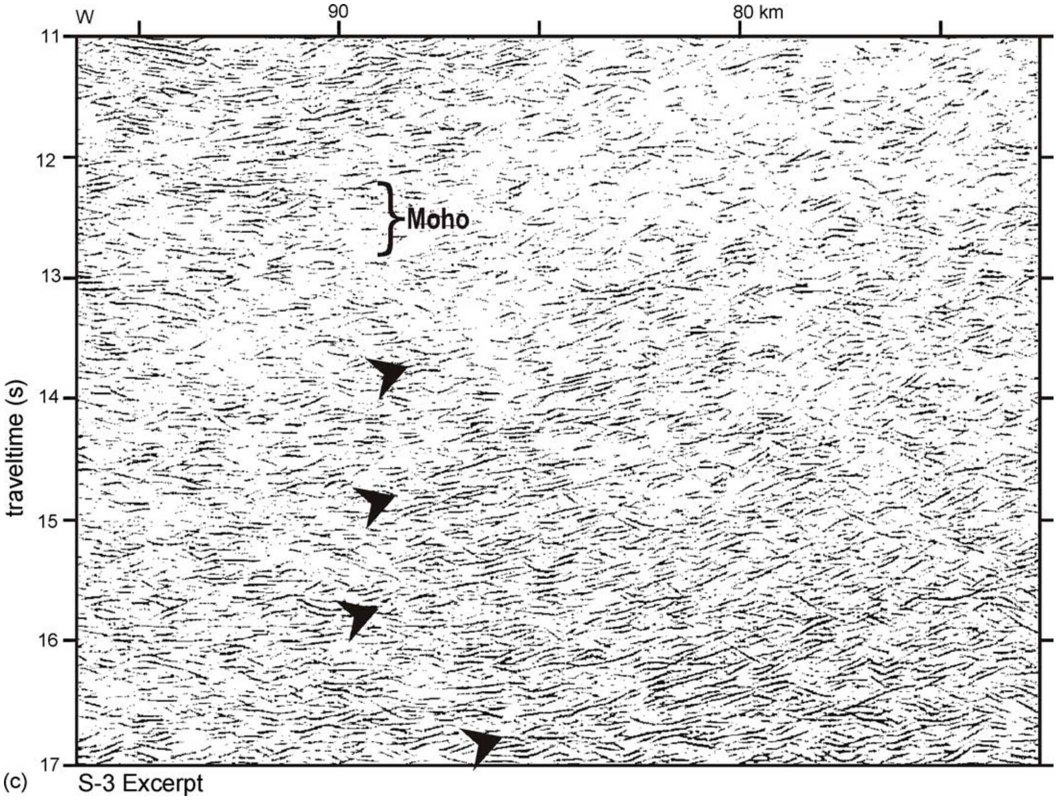


Fig. 9. (*Continued*).

of 16.5 km and unmigrated apparent dip of about 20° south (assuming 8.1 km/s). Further south along the profile (Figs. 6a and 11) a less prominent reflection group ("b") comes in at 16.45 s (56.3 km depth), collinear with "a", and thus is likely a southward extension of it. Still further south, a third almost collinear reflection segment ("c") arrives as "deep" as 17.6 s below 40–60 km (Fig. 6a). The main traveltime interval of the unmigrated reflection, 15.0–18.0 s, corresponds to a migrated interval of ∼12.7–15.0 s, after correcting for obliquity, which places the uppermost part of the reflector at just sub-Moho; the deepest extent of the reflector is not constrained, since the mantle reflections disappear into the cross-correlation noise beyond about 18 s. Again invoking a straight-ray approximation, the migrated dip, corrected for obliquity, of the mantle reflector on S-1 would be about 40°.

On the southernmost east–west line S-2, a 5.5 km long subhorizontal mantle event ("d") appears at approximately 14.75 s (49.4 km depth) below 85 km (Figs. 6b and 7a). This arrival is complex and appears to be largely, but not entirely, diffractive. This arrival is corroborated by the nearby COCORP Illinois Line 1, which shows a very similar feature at about the same traveltime (Fig. 7a). A longer series of planar (not diffractive) mantle reflections appears further east at "e", extending from 15.5 to 17 s (53–59 km) just beneath the intersection of lines S-2 and S-1 (Fig. 12). This series dips apparently 16° west, extends for a length of 10.6 km, and is collinear with a deeper set of fainter reflections to the west arriving beneath 65 km (Fig. 12). This series correlates in time (unmigrated) exactly with the longer south-dipping reflections observed from S-1 and thus provides corroboration as well as cross-line control. The mantle reflection image on S-2 is more complex and consists of four or five distinct, mostly west-dipping, segments (Fig. 12). On both orthogonal profiles, the mantle reflection appears as an isolated feature, surrounded by a mostly reflection-free section (see especially coherency-filtered S-1 section (Fig. 11b)), and continues up to the Moho only after migration with an obliquity correction.

Along profile S-3, prominent mantle reflectivity is also observed, but at lesser traveltime (Fig. 9). This would be consistent with a single surface approximation since the mantle reflection sequence on the north–south line S-1 dips up to the north in the line of profile (Fig. 6a). On S-3, reflections begin to arrive just after the Moho, centered below 52 km and dip more steeply into the

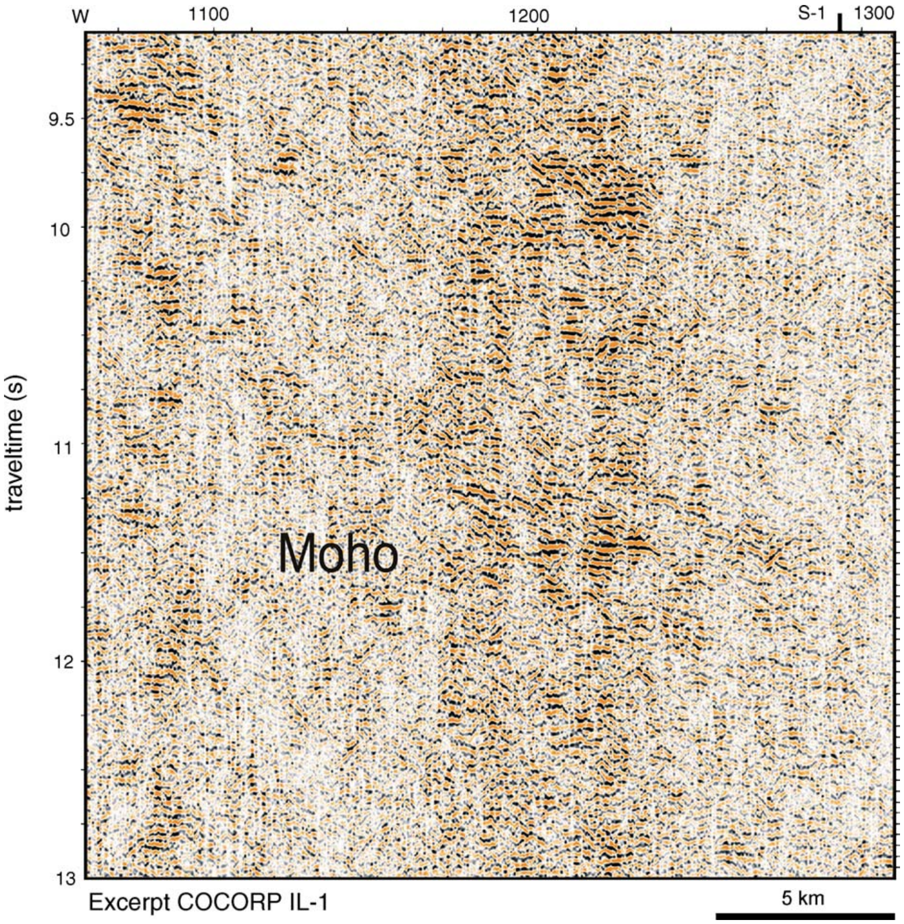


Fig. 10. Excerpt section from COCORP seismic profile IL-1 illustrating the Moho discontinuity as occasional reflections and a cessation of crustal reflectivity. Note also the severe "column effect" on the COCORP data. S-1 indicates the intersection of seismic line profile S-1.

mantle (Fig. 9). The mantle reflection group here ("g") dips from just beneath a horizontal Moho level, and then extends to about 14 s (46.4 km depth) with a length of 22 km. The reflection group is however not clearly imaged for its entire length and different segments make up a sequence of events with a more or less uniform orientation at an apparent dip of 21° west (Fig. 9). This sequence projects westward directly into a deeper, but more limited zone, of west-dipping mantle reflections (Figs. 6c and 9c), implying a much larger extent than that shown only in Fig. 9a and b. Where this sequence projects toward the intersection with S-1, a few poorly resolved south-dipping reflections appear on S-1 at the expected traveltimes (Fig. 6a). Looking to the east, the "g" reflection group is collinear with, and thus perhaps related to, a dipping sequence in the lower crust (Fig. 6c). Because the S-3 sub-Moho reflections are so close in time to the Moho level of 12.0–12.5 s and has a lower apparent velocity relative to the reflection on S-1, we have produced migration spectra for this part of the profile using velocities of 0 (no migration), 6 km/s (bulk crust value), and 8 km/s (bulk uppermost mantle value, Fig. 13). Crustal events (the Moho and a diffraction pattern, Fig. 13) migrate properly at 6 km/s and are clearly overmigrated at 8 km/s. On the other hand, the sub-Moho events remain planar at 8 km/s and remain just below the Moho level (Fig. 13) and indicates these events are not diffractions. Accounting for obliquity like above, the unmigrated traveltime interval of 14.0–17.0 s corresponds to a migrated interval of 11.5–13.6 s, which means that the reflector probably begins in the lower crust, penetrates the Moho, and then plunges into the mantle. Unlike the mantle reflection for S-1, a thick sequence of reflections appears beneath the onset of the dipping reflectivity as shown in Figs. 6c and 9. A straight-ray approximation gives a corrected migrated dip of about 50°. The obliquity-corrected migration would move the mantle reflector a lateral distance of about 26 km to the east and north,

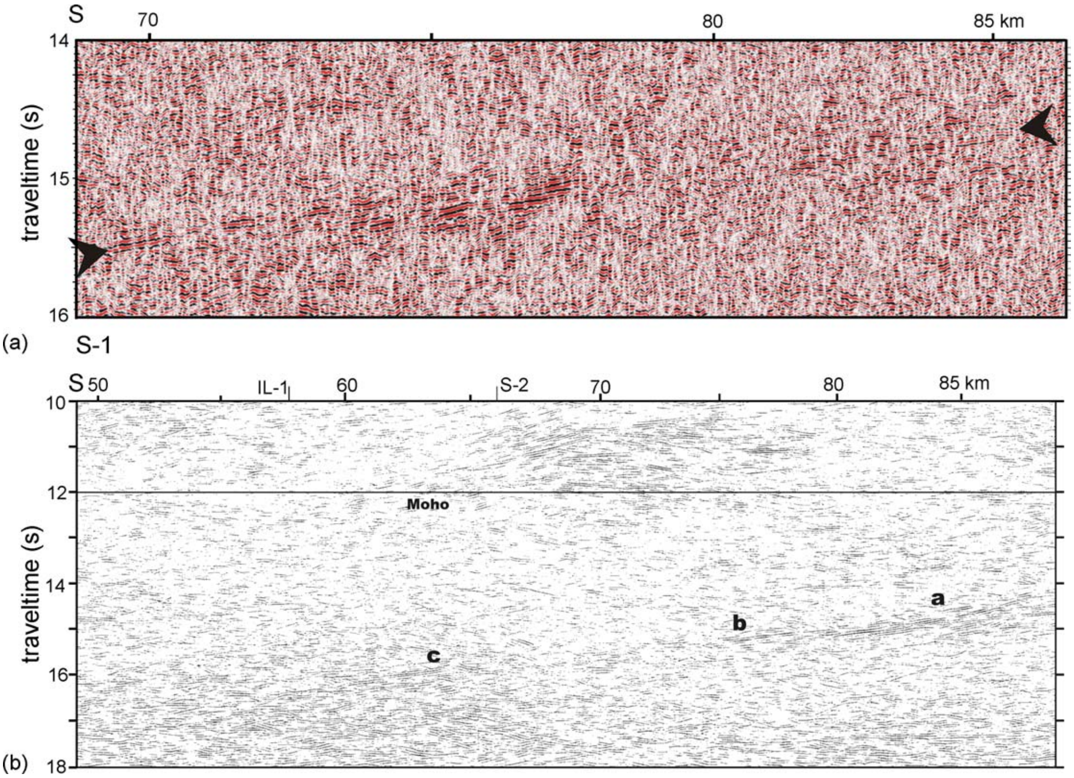


Fig. 11. (a) Excerpt from profile S-1 illustrating mantle reflection “a” (unmigrated). (b) Excerpt from profile S-1 showing migrated mantle reflections, with coherency filter applied (i.e. as applied in Fig. 9b). The 12-s time line, which corresponds to the expected Moho arrival time (Fig. 3), is plotted.

for unmigrated traveltimes of 14 and 15 s, respectively (using formulation reviewed in Li and Eaton (2005)).

3.4. Results of 3D inversion of Bouguer gravity data

In order to provide some constraints on the interpretation of the reprocessed seismic profiles, we performed a controlled 3D inversion of regional Bouguer gravity obtained from the US Geological Survey for the study area and vicinity based on the technique of Parker and Huestis (1974). The Bouguer gravity data were first gridded and then smoothed using a low-pass (cut-off wavelength = 150 km; 8th order filter) Butterworth filter. The low-pass filter was performed in order to reduce the effects of shallow crustal sources. A forward model was then computed using a depth-to-basement (obtained from the Illinois State Geological Survey) estimated by adding 1 km depth to the top of the Ordovician Trenton Formation marker in borehole logs and assuming a crustal thickness of 39 km (Fig. 14). The additional 1 km

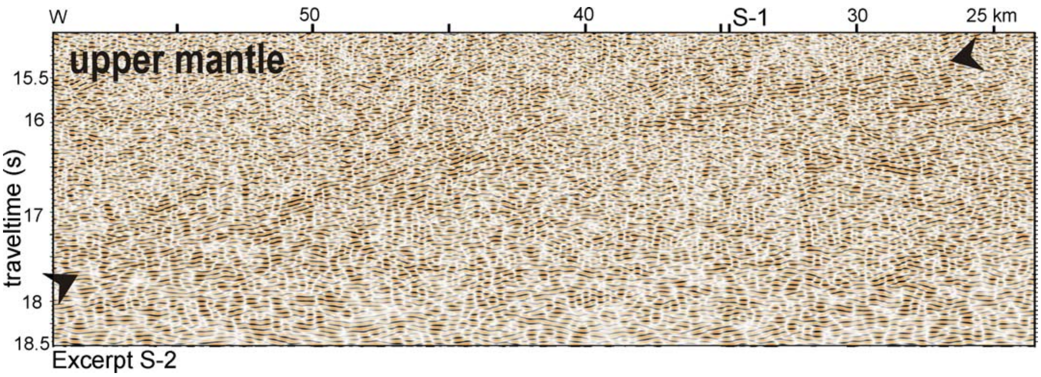


Fig. 12. Excerpt of S-2 showing migrated mantle reflection near its intersection with S-1.

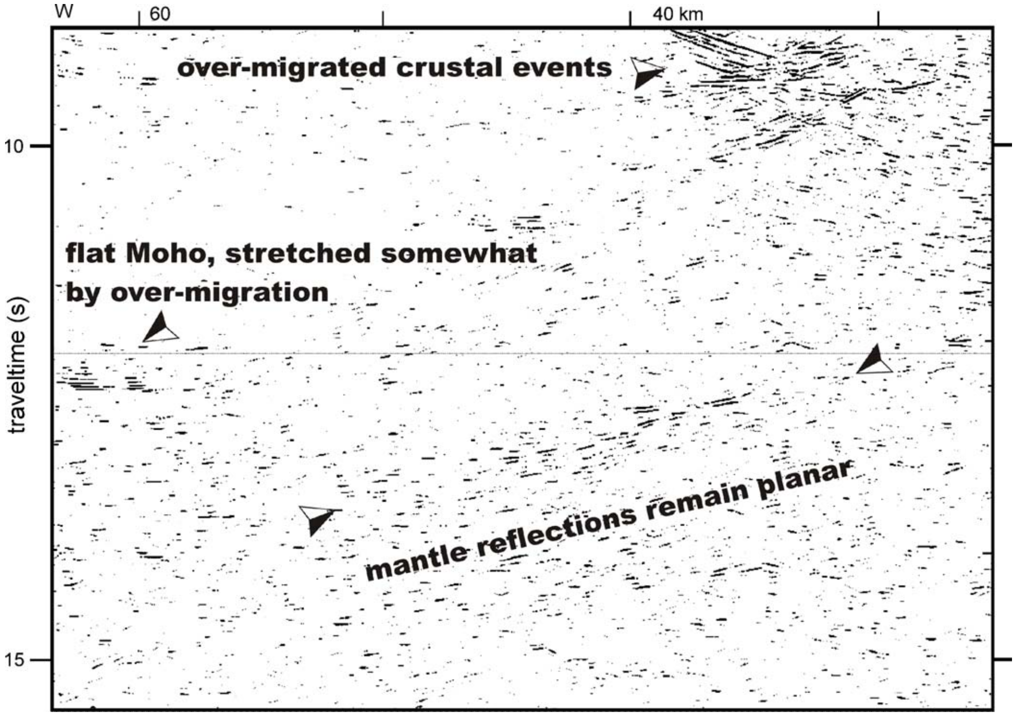


Fig. 13. Excerpt of S-3 migrated at a constant velocity of 8 km/s, appropriate for the uppermost mantle. The expected behavior of crust, Moho, and deep "planar" events for this migration velocity is noted. The data are displayed with a coherency filter as in Fig. 9b.

depth probably underestimates the depth to basement in most areas, but this would mostly only affect the magnitude of the inverted densities and not their shape. The inversion was allowed to range over the upper mantle layer (39–100 km) with an initial density of 3.40 g/ml while keeping structural boundaries constant. In our inversion, we have attempted only to model the long-wavelength portions of the field (thus, the non-exact fit between calculated and observed values in Fig. 14b). The results (Fig. 14) show a general northeast trend of high density in the mantle layer. Part of this trend corresponds to the position of the mantle reflection. Although the trend of the reflection is actually orthogonal to the long-wavelength, northeast trend of the density anomaly, the reflection trend does match in a general way part of the northeast trend defined by an isolated high in density in eastern Illinois when the migrated reflection position is accounted for (Fig. 14b). The migrated version of the mantle reflectivity would shift the anomalous mantle to the northwest (Fig. 14b). We have also computed a map of residual magnetic intensity (Fig. 14c), which represents mainly crustal components, of the same area so as to be able to assess the degree to which crustal compositional patterns correspond to the mantle density anomaly (Fig. 14b). Some similarity in pattern is apparent between the two maps in the vicinity of the mantle reflector (beneath its unmigrated position), which suggests that compositional variations in the crust above the mantle reflection may be linked in some way to mantle variations. On the other hand, the long-wavelength density trend (dashed line on Fig. 14c) shows no apparent correlation with magnetic anomalies.

4. Discussion

4.1. Mantle reflectivity beneath the Illinois basin

Considering the rarity of mantle reflections on dedicated deep reflection profiles in the USA (Best, 1990), the imaging of mantle reflections on the reprocessed industry profiles from the Illinois basin is remarkable. Mantle reflections observed from common depth-point data are infrequent, especially in the USA, where thousands of kilometers of dedicated deep reflection profiles have been acquired during the past 30 years. The only significant case of sub-Moho mantle reflectivity beyond the Illinois basin in the USA is from COCORP profiles over the Williston basin, which have been interpreted to show dipping and subhorizontal reflections within the uppermost mantle (Baird et al., 1995). The unusual expression of mantle reflections beneath the Illinois basin may be related to the unusually high Lg

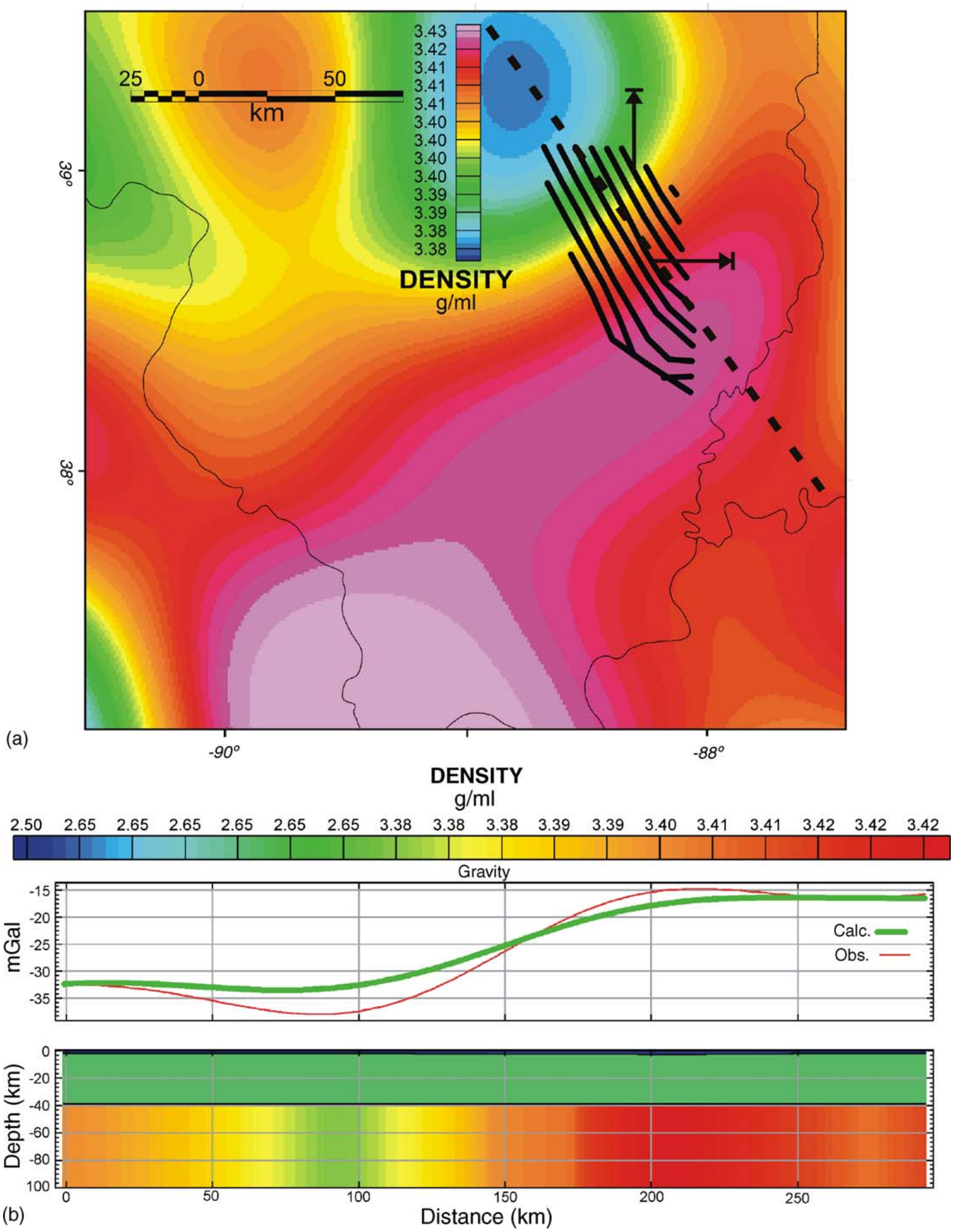


Fig. 14. (a) Map of mantle density anomalies (see text for explanation). Mantle reflection pattern is shown along with arrows indicating migrated position (see Fig. 1b for close-up of contours and labeling). Dashed line shows cross-section location in (b). (b) Cross-section of density structure along the line of profile shown on map in (a). (c) Map of residual magnetic intensity produced by computing an upward continuation of 2000 m, that is then subtracted from the observed. The light dashed line cutting across most of the map represents the northern limit locally of anomalous high-density mantle as computed from inversion of Bouguer gravity data (a).

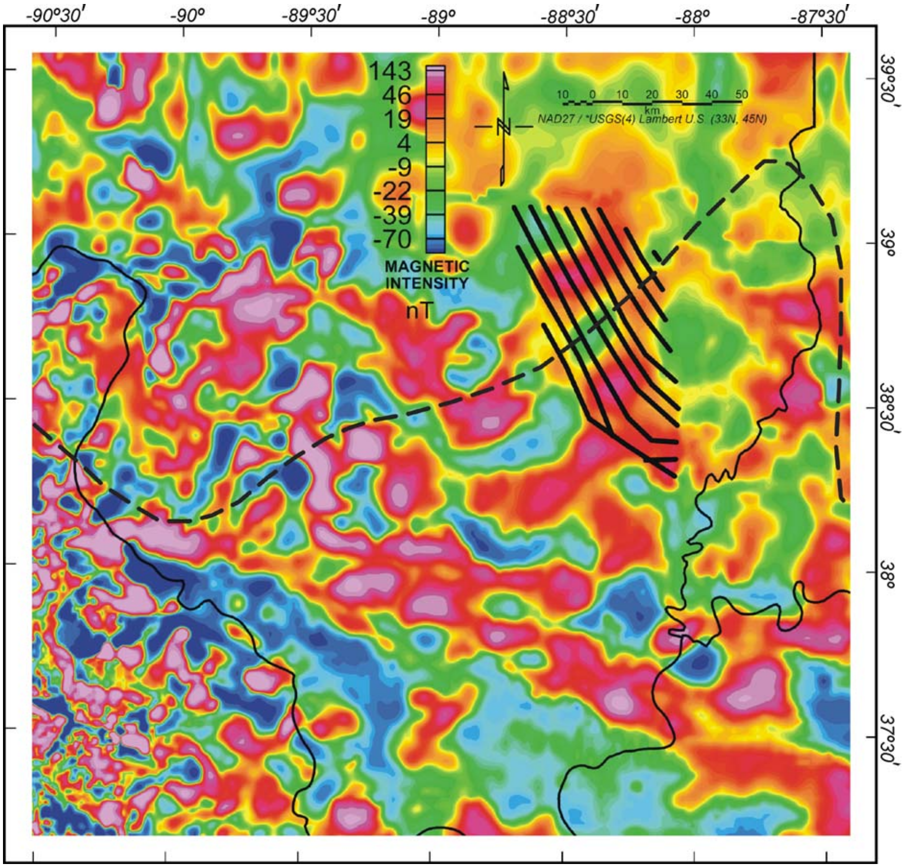


Fig. 14. (*Continued*).

coda Q (at 1 Hz) for the crust in the central Midcontinent (Baqer and Mitchell, 1998; Mitchell and Jemberie, 2001) or to the superior imaging related to the relatively broad vibroseis frequency band (14–126 Hz) (Fig. 4) and long-record (20 s) source. A high Lg coda Q corresponds to low attenuation of sound and consequently, higher quality image resolution. In order to readily compare Q structure for the study area and vicinity, we have gridded the original Q values from Baqer and Mitchell (1998) (Fig. 15). As can be seen from comparing these results with Fig. 1a, the northeast trend of higher Q values approximately follows crustal structural trends. Lg coda Q values for the study area are about 650 and characterize a rather restricted region of high Q centered over the Illinois basin and nearby areas between Missouri and Ohio (Fig. 15). The only other area of the conterminous USA where Q values approach or exceed those of the study area are in the New York–Pennsylvania region. Mantle reflections could thus possibly exist in other parts of the USA continental lithosphere where deep seismic reflection profiles have been surveyed, but cannot easily be imaged due to high attenuation. However, we also note that beneath the Williston basin, where mantle reflectors have been interpreted (Baird et al., 1995), Q values are actually anomalously low.

The mantle reflections, which appear as isolated events in an otherwise non-reflective uppermost mantle, cannot be uniquely correlated to any particular known geologic surface feature. Therefore, reaching a unique interpretation is difficult. A similar ambiguity exists for strong mantle reflections observed on a 50-s explosive source reflection profile over the southern Ural Mountains that are interpretable as either being preserved from the original Paleozoic deformation of the orogen or representing an unknown younger structural and thermal process that did not perceptibly affect the overlying crust (Knapp et al., 1996). Due to the virtual lack of basement or even Paleozoic bedrock outcrops for the Illinois basin, we must rely on limited drillhole-derived information in order to provide some constraints for interpreting the mantle structure. The emplacement of igneous rocks of the granite–rhyolite province has been associated with both compressional (subduction-island arc systems) and extensional (rift) regimes, which involve

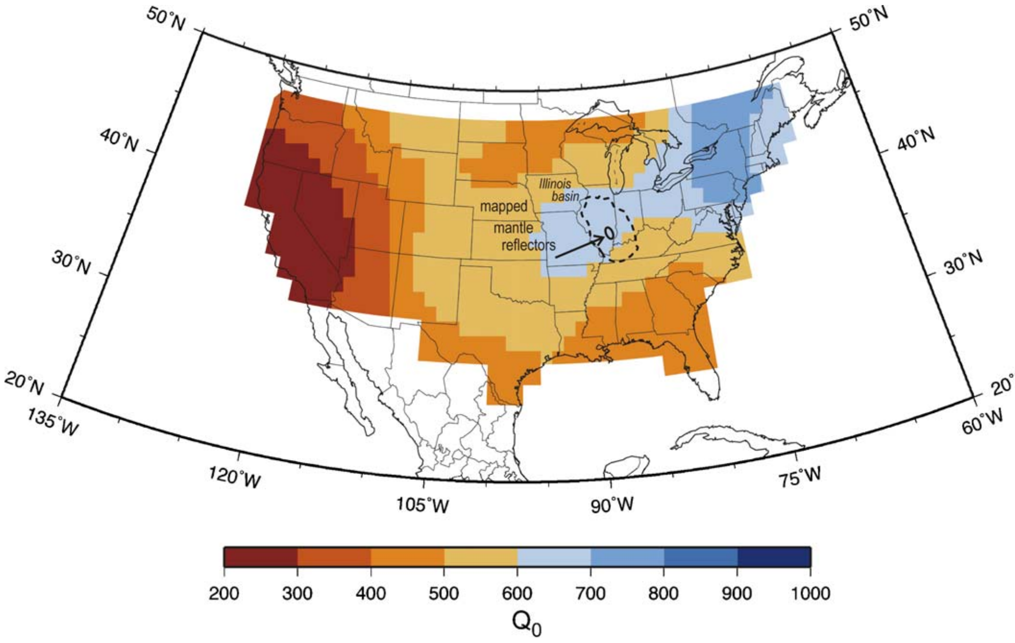


Fig. 15. Map of gridded values of Q (seismic quality factor) from digital data provided by Baqer and Mitchell (1998) using a $2^\circ \times 2^\circ$ cell size. Enclosed contour pattern in center of map (southern Illinois) represents mantle reflection mapped from the reprocessed seismic reflection profiles (see Fig. 1b for close-up of contours and labeling). This figure is provided courtesy of Prof. Brain J. Mitchell and Dr. Saadia Bager and is used with their kind permission.

plate tectonic processes that may create reflection structure within mantle lithosphere. We also appeal to better constrained analogs for mantle reflection interpretations from the North Sea, western Canada, and the Baltic Sea (Cook and Vasudevan, 2003; Snyder and Flack, 1990; BABEL Working Group, 1993).

4.2. Analogs for mantle reflectivity

Cook et al. (1998) and Cook and Vasudevan (2003) have interpreted dipping mantle reflections from beneath the Precambrian Slave Province and Wopmay Orogen of northwestern Canada to be remnants of a Proterozoic subduction zone based on their projection up into a mapped relict Mesoproterozoic subduction structure. Based on geometric relationships of the upper mantle reflections to the subduction zone and the Moho, three interpretations were proposed: (1) shear zones within ultramafic rocks; (2) layered metamorphic rocks; or (3) igneous intrusive layers. As pointed out by van der Velden and Cook (2005), most of the mantle reflections in Canada dip beneath and toward an older cratonic mass. For the well-studied “Flannan” and “W” dipping mantle reflections (e.g. Fig. 16) north of mainland Scotland and Ireland, Warner et al. (1996) suggested that the geometry, modeled physical properties, and geologic setting of the reflections indicate fragments of eclogitized oceanic crust. The mantle reflectors would thus be relicts of a pre-Caledonian oceanic subduction now preserved in the continental lithosphere. Alternatively, Flack et al. (1990) and Reston (1990) interpreted the “Flannan” and other mantle reflectors beneath the margins of rift basins of the North Sea area in terms of Mesozoic rifting processes (e.g. ductile extensional shear zones in upper mantle). Beneath the northern Baltic Shield near the Proterozoic–Archean boundary (BABEL Working Group, 1990), dipping mantle reflections can be traced upward to the Moho or into the lowermost crust and are interpreted to represent relict subducted Precambrian ocean crust.

4.3. Constraints from basement geology

The eastern granite–rhyolite province that underlies much of the Illinois basin has been described by Lidiak (1996) as part of a 3000 km long belt of post-1.6 Ga mainly felsic igneous rocks that extends across much of North America (Fig. 1a), which consists mainly of epizonal to mesozonal granite and related rhyolite that was extruded on or emplaced within the older Proterozoic rocks. These felsic igneous rocks have A-type (anorogenic) chemical affinities and accumulated in a within-plate environment, part of a mid-Proterozoic supercontinent at 1.5 Ga. The felsic rocks are associated with

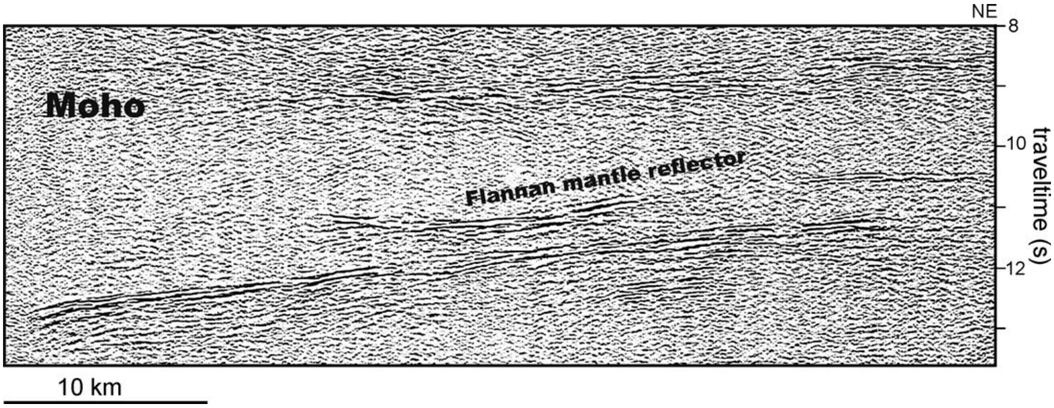


Fig. 16. Excerpt from BIRPS WIRE 4B deep unmigrated seismic reflection profile from offshore north of Ireland (Klemperer and Hobbs, 1991).

subordinate within-plate tholeiitic basalt, which implies magmatism associated with crustal extension in mid-Proterozoic time, or implies magmatism associated with a Proterozoic "hot spot" which would account for their vast occurrence. All of the rocks are essentially unmetamorphosed, and none are penetratively deformed.

Various explanations have been put forward for the granite–rhyolite province that are based on plate boundary processes. Geochemical analyses by Nelson and DePaolo (1985) and Lidiak (1996) suggest that the felsic rocks were sourced from partial melting of lower continental crust. Similarly, a thermal response to rifting and extension along a passive continental margin followed by continental collision and large scale mantle up-welling has been proposed (Aberg, 1988; Windley, 1989; Hoffman, 1989b). Alternatively, Bowring et al. (1988, 1991) and Van Schmus et al. (1996) suggest a mantle source region for the granites and rhyolites to lie just south of a boundary defined by Nd isotopic data extending from southeast Oklahoma northeastwards to central Indiana, inferred as the southeastern limit of pre-1.6 Ga crust (Fig. 1a). This isotopically defined boundary thus represents a Proterozoic continental margin situated just north of our region of mapped mantle reflectivity (Fig. 17). Felsic rocks south of this boundary thus represent 1.5 Ga material of juvenile mantle origin, such as that possibly derived from a continental magmatic arc along a convergent continental plate boundary and thus implying direct crust–mantle interaction (via subduction) (Van Schmus and Bickford, 1981; Van Schmus et al., 1996). Menuge et al. (2002) proposed that the rhyolites may have formed in an extensional back arc setting within the continental plate overlying an active or recently active, subduction zone. Furthermore, Rivers and Corrigan (2000) noted that many of the features of the Mesoproterozoic geology of southeastern Laurentia can be explained as the product of arc and back arc evolution rather than anorogenic processes such as anatexis. Van der Lee (2001) argued from earthquake tomography that plate tectonic processes may have been active in North America since about 3.0 Ga (Archean) with what she referred to as "protoplates" that were much smaller than present-day tectonic plates. She inferred that the Laurentian continent, the predecessor of the North American continent, was assembled by subduction at about 1.0 Ga. In a general way, the study area lies along the southeastern border of the Archean and older Proterozoic provinces of Laurentia, as defined by Van der Lee (2001) (Figs. 1a and 17). Heigold and Kolata (1993) postulated a Proterozoic crustal boundary based on exploration geophysical data cutting across the southern Illinois basin (Fig. 17).

4.4. Hypothetical origin for lower crustal and upper mantle reflectivity beneath the Illinois basin

The geological scenarios described above imply that an ancient rifting or subduction environment existed along the margin of a Precambrian supercontinent in which upper mantle may have been deformed or altered. For the subduction scenario (Fig. 18a), accreting crustal material could have been thrust or imbricated into the mantle during plate collision. Our observed mantle reflectors could accordingly be considered to be shear surfaces. Proterozoic reconstructions described by Van Schmus et al. (1996) and Schneider et al. (2004) for the USA Midcontinent are suggestive of northwestward subduction. For this hypothesis, our observations of a mantle reflector dipping to the southwest would therefore imply localized complexity along the ancient continental margin beneath the present-day Illinois basin or a local reversal in subduction polarity. A model of the

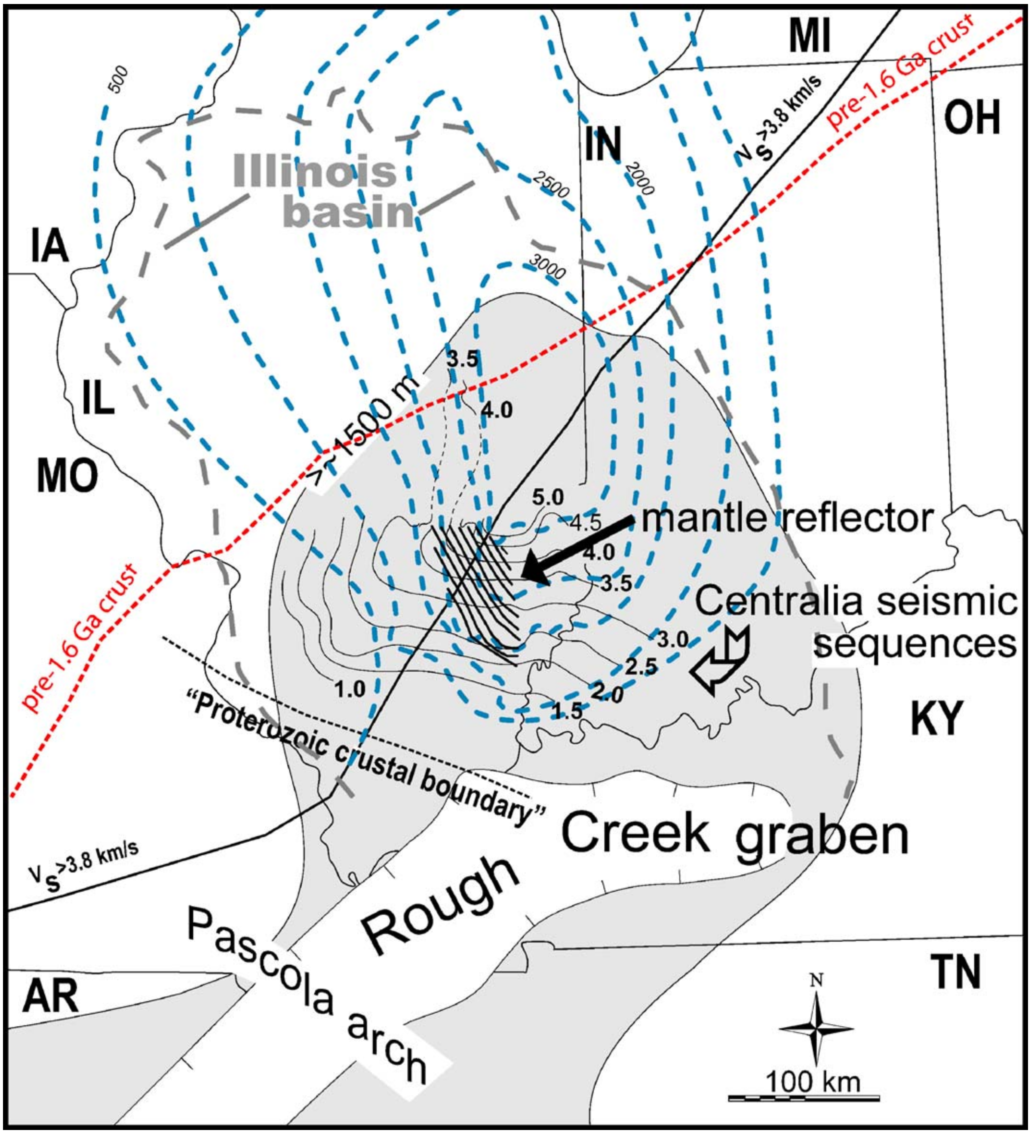


Fig. 17. Contour relationship map illustrating the consistency between mantle reflection contours and those of the Proterozoic seismic stratigraphic sequences and Paleozoic Illinois basin when superimposed. Shading indicates Paleozoic strata thicker than ∼1500 m (modified from Kolata and Nelson (1991)), which approximates the early cratonic phase of the basin. The thick solid contours represent the mantle reflection pattern (Fig. 1b) while the thinner solid lines are isotraveltime (s, migrated) contours to the base of the entire Proterozoic seismic sequence ("Centralia sequence" originally from Pratt et al. (1992)) from McBride et al. (2003). The dashed blue line represents the thickness (in feet) for the Cambrian Mt. Simon Sandstone of the Illinois basin (from McBride et al. (2003)). Other geological and geophysical boundaries (see Fig. 1a) denote a major plate tectonic or continental margin during the Proterozoic, as discussed in the text. "Proterozoic crustal boundary" is from Heigold and Kolata (1993).

convergence of an island arc terrane and southward subduction of transitional continental-oceanic crust along the southeastern margin of Laurentia (Fig. 18a) could also explain a southwestward dipping mantle structure. In this case, the mantle reflectors could represent the arrested subduction of oceanic-transitional crust just outboard of the Proterozoic continental margin (Fig. 18a). This scenario is roughly analogous to the arrested subduction of continent-oceanic crust dipping away from the northern Australian continent and beneath the Banda arc (e.g. Snyder et al., 1996).

An alternative to the subduction hypothesis for the study area is lithospheric delamination (Knapp et al., 2005) (Fig. 18b), which involves loss of material from the base of the lithosphere by gravitational instability (Bird, 1979), detachment of oceanic slabs (Sacks and Secor, 1990), or foundering of a mafic lower crust and/or upper mantle by phase changes (Nelson, 1991, 1992; Kay and

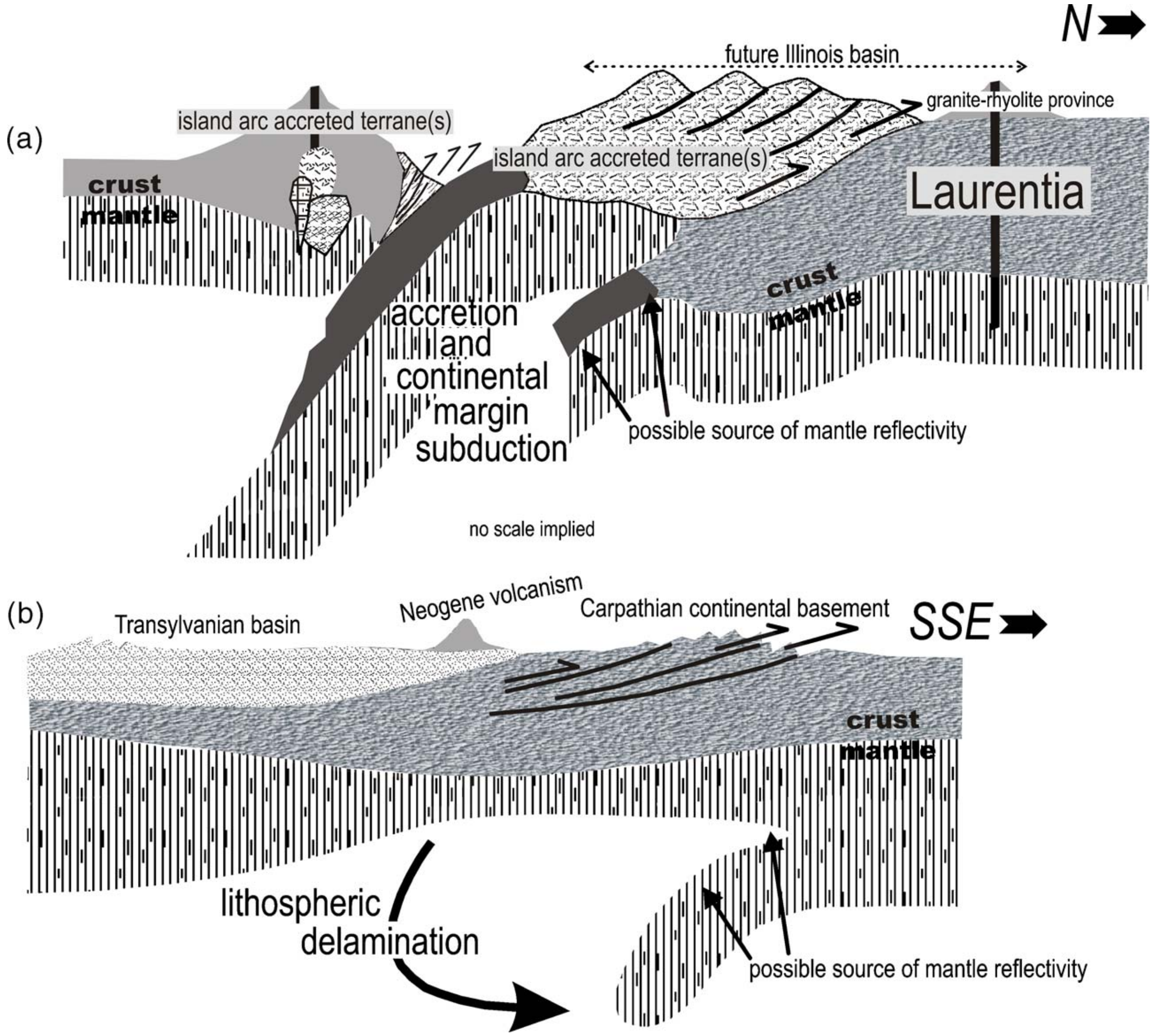


Fig. 18. Speculative tectonic cartoons that may explain preserved mantle reflectors beneath the present-day Illinois basin. (a) A generic island-arc converging with the Laurentian supercontinent about the time of granite–rhyolite production in the USA Midcontinent (~1.4–1.5 Ga) (adapted and redrawn from the generic model shown by Lynn S. Fichter, James Madison University). (b) Model for present-day lithospheric delamination beneath the Vrancea zone near the Carpathian Mountains in Romania (based on Knapp et al. (2005)).

Kay, 1993). Nelson (1992) suggested that the mantle part of the lithosphere beneath the continents is negatively buoyant with respect to the underlying asthenosphere and therefore, if a suitable flaw existed, might peel away from the overlying crust and founder into the deeper mantle. A delamination episode could therefore have produced structure within the lower crust or upper mantle preserved today as dipping reflectors (Fig. 18b). The heating consequent to delamination would be due to the combined effects of emplacing hot asthenosphere against or near the base of the crust and intrusion into the lower crust of basaltic magma produced by decompression melting of the asthenosphere, which must rise to replace the foundering lithospheric root. This could have then have led to the intrusion/extrusion of the granites and rhyolites beneath the Illinois basin derived from partial melts due to relative buoyancy. A possible contemporary analog might be found in the Vrancea Zone near the Carpathians in Romania where a dipping zone of seismicity in the mantle can be explained as active delamination of lower crust into the mantle (Fig. 18b), as opposed to active subduction (Knapp et al., 2005).

In the above two interpretations, the mantle reflectors could represent either “scars” of delamination in the form of intact pieces of former lower crust that has been partially detached or the remains of slab imbrication as shown, for example, by Cook et al. (1998) for western Canada. The observation and modeling of the corrected orientation of the deep reflectors on S-3 cutting through the lower crust, across the Moho, and continuing into the upper mantle are suggestive of some kind of imbrication of mantle and/or lower crustal material.

4.5. Relation of mantle reflectivity to subsidence of the Illinois basin

The anomalous mantle reflectivity is localized beneath the deepest part of the Illinois basin north of the Reelfoot rift (Figs. 1a and 17) as well as beneath the steep southern flank of the Cambrian Mt. Simon depocenter and underlying Proterozoic seismic stratigraphic sequences (Figs. 2 and 17). As shown by comparison with the Middle Ordovician Trenton Formation (Fig. 2b), the mantle reflectors lie approximately beneath a north-directed elongation of the middle Paleozoic depocenter. We therefore speculate that the upper crustal features could be associated either with processes that originally formed the mantle reflectors or with the static effect of the mantle reflectors themselves, perhaps as a buried load of higher density material that influenced subsidence of the basin. The gravity inversion results indicate a present-day local lateral density contrast in the mantle of about 0.03 g/ml (i.e. from a high to low value of 3.42–3.39 g/ml) partially corresponding to the area of the mantle reflector (Fig. 14a). On Fig. 2, we show the outline of the northern edge of positive mantle density anomaly, part of which matches the depocenters of the Proterozoic stratigraphic sequences referred to above. This correspondence further supports an interpretation that the reflectivity and density anomaly in the upper mantle is genetically linked to the localization of Proterozoic and early Paleozoic depocenters.

McBride et al. (2003) suggested that the Proterozoic reflective sequences buried within the upper crust represent either a collapsed caldera complex or an irregularly shaped rift basin, either of which could be related to the production of the granites and rhyolites of the eastern granite–rhyolite province that underlies the Illinois basin. This interpretation accords well with the idea that the basin overlies a crust and uppermost mantle that underwent significant thermo-magmatic activity, which provides a context for interpreting the unusual occurrence of mantle reflectivity here. Superimposing the contours of the basal Cambrian unit of the Illinois basin and deeper sequences on the mantle reflector contours (Figs. 2 and 17) shows a limited degree of parallelism. The fact that the mantle reflector pattern observed for our study roughly mimics Paleozoic and shallow basement sequence trends suggests that a structurally anomalous mantle may have exerted some control on subsidence processes for the Illinois basin and any Proterozoic precursor structures. McBride et al. (2003) proposed that the upper crustal Proterozoic sequences acted as a precursor to the very early part of the Illinois basin subsidence during the deposition of the Cambrian Mt. Simon Sandstone (Fig. 17), after which subsidence shifted to the south over the Reelfoot rift (Fig. 1a). We suggest in like manner that the mantle reflector pattern may have played an analogous role; however, the actual controlling mechanism is not yet clear.

Baird et al. (1995) previously documented a case of dipping reflections beneath the northern Williston basin in Montana and North Dakota from COCORP deep reflection profiles interpreted as mantle in origin although no Moho reflection was identified. The Williston basin is in many ways analogous to the Illinois basin in having an elliptical outline and possessing no obvious underlying rift or major basin-bounding normal faults. Baird et al. (1995) suggested that the interpreted mantle reflections represent a preserved crustal root of previous Precambrian collisional orogeny (Hudsonian), now preserved as remnant crustal “keel” that underwent eclogite-facies metamorphism, which then overprinted the base of a now non-reflective lower crust. The concomitant metamorphic phase change in the lower crust could be a cause for subsequent Paleozoic basin subsidence (e.g. Hamdani et al., 1994). In like manner, Fowler and Nisbet (1985) explained the subsidence of the basin as due to eclogitization of a mafic sub-crustal body. In a third example, Eaton et al. (2000) interpret layered lower crustal and upper mantle reflectivity beneath the Rocky Mountain foreland in southwestern Alberta as eclogitized mafic lower crust. Thus, the combined observation of a large sub-crustal reflection, a partially corresponding high-density mantle anomaly, and the localization of a Proterozoic and an early Paleozoic depocenter of the Illinois basin suggests a similar explanation involving an eclogitized mafic sub-crustal body.

5. Conclusions

This study presents the results of reprocessing several hundred kilometers of industry seismic reflection profiles in which the original 4 s records were extended to 20 s. In this way, ordinary industry reflection data were transformed into deep seismic profiles penetrating as deep as the uppermost part of Earth's mantle. Beneath the Paleozoic sedimentary strata of the Illinois basin lie layered Proterozoic basement sequences. Isolated dipping reflectors exist within the mantle lithosphere beneath these sequences and constitute one of the first observations of mantle reflectivity in the continental USA and the first with 3D control. Based on similar occurrences of uppermost mantle reflectors in other parts of the world and based on the character and attitude of mantle reflectors observed in this study, a lithospheric plate subduction is proposed as one possible origin. Convergence of an island arc terrane and southward subduction of transitional continental-oceanic crust along the southeastern margin of Laurentia in Proterozoic time could have produced structures preserved today as relict mantle "scars" (Fig. 18a). The occurrence of granites and rhyolites with properties indicative of formation in an extensional back arc setting within a continental plate overlying a subduction zone supports this possibility. The probable existence of plate tectonism in general as early as 3.0 Ga also supports this as does the location of the southern border of the supercontinent of Laurentia near the study area. However, certain anticipated subduction related evidence is not seen, such as metamorphism and associated deformation.

An alternative process involving lithospheric delamination of mantle lithosphere resulting from Proterozoic terrane collision and accretion is also consistent with geological and geophysical data. The intrusion/extrusion of the granites and rhyolites in this case could be related to melting caused by lower crustal magmatism resulting from decompression associated with delamination. The presence of a flat Moho and the absence of crustal roots beneath the present-day Illinois basin are suggestive of crustal flow, a process resulting from delamination; however, a well-expressed and continuous Moho, as might be expected from delamination, is not observed.

The correspondence between the mantle structure, a portion of a mantle density anomaly, and late Proterozoic and early Paleozoic basin depocenters points to a common cause for the mantle reflectors and processes leading to the development of overlying features in the crust. In this way, the mantle reflectivity and density anomaly could have acted as a "buried load", originating from eclogitization of subducted or delaminated mafic lower crust, which influenced subsidence of the basin. We mention possible mantle eclogitization briefly as a candidate mechanism for explaining both the mantle reflectors and the observed localization of Paleozoic basin and Proterozoic sequences. More complete explanations for this type of mechanism for analogous cases are presented in Fowler and Nisbet (1985), Baird et al. (1995), and Eaton et al. (2000). Testing this hypothesis further will require detailed information on seismic velocity obtained from a dedicated wide-angle seismic program in the Illinois basin.

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