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UPPER MANTLE REFLECTIVITY BENEATH AN INTRACRATONIC BASIN: INSIGHTS INTO THE BEHAVIOR OF THE MANTLE BENEATH THE ILLINOIS BASIN

by

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A thesis submitted to the faculty of Physical and Mathematical Sciences

Brigham Young University

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GRADUATE COMMITTEE APPROVAL

Of a thesis submitted by

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This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read this thesis of Maxwell S. Okure in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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ABSTRACT

UPPER MANTLE REFLECTIVITY BENEATH AN INTRACRATONIC BASIN: INSIGHTS INTO THE BEHAVIOR OF THE MANTLE BENEATH THE ILLINOIS BASIN

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Master of Science

Reflectivity images of the lower crust and uppermost mantle beneath the 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 travel time. The reconstructed bandwidth includes frequency components suitable for imaging structures from signals received from both sedimentary basin reflectors and those received from reflectors in the deep crust and upper mantle. Mantle and sub-Moho reflectors are imaged down to 18 s two-way travel time (~62 km) and are observed on intersecting profiles generally 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 upper mantle heterogeneity, relative to other parts of the USA studied using reflection methods. The relatively isolated occurrence of mantle 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 basement rocks, effectively 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 arc to the pre-1.6 Ga southern margin of the Laurentian continent.

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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; Cook et al., 1999), as well as beneath contemporary plate 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). Not surprisingly, mantle reflectors are most commonly explained in the context of subduction processes (e.g., Warner et al., 1996). Mantle reflectors have accordingly been interpreted as shear surfaces associated with the subduction of one lithospheric plate beneath another (Synder and Flack, 1990; Cook and Vasudevan, 2003). Such interpretations are often supported by the orientation of the mantle reflector(s) with respect to lower crustal reflectivity. For example, dipping mantle reflectors with an orientation that is similar to known compressional belt at the surface may be reasonably interpreted as compressional in origin.

The purpose of this study is to present the results of reprocessing of industry vibroseis seismic reflection profiles for expected mantle travel times from the Illinois basin that reveal some of the first clear dipping sub-Moho and mantle reflectors in the USA. Seismic reflectivity within the upper mantle lithosphere is a very uncommon feature throughout the world. Our study provides a rare opportunity to observe and study signatures of ancient mantle processes in an intra-cratonic basin context. Understanding the development of this reflectivity will provide greater insight into upper mantle processes in a poorly known area of Precambrian lithosphere beneath a presently stable craton. We will also suggest a mechanism that may have contributed to the subsequent early Paleozoic development of the Illinois basin.

Regional Setting

Geology

The Illinois basin (Fig. 1) 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, 1990) 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 (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 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 terrane commonly referred to as the Eastern Granite-Rhyolite Province (Fig. 1). This province has been described as either a few-kilometer thick veneer or isolated igneous intrusions that are part of a large igneous province extending from northern Mexico to eastern Québec (Lidiak, 1996; Karlstrom et al., 1999). The basement rocks have been interpreted as anorogenic igneous based on geochemical analyses, the lack of metamorphism commonly associated with convergent plate boundaries, and the absence of deformation (Bickford et al., 1986). The lack of basement rocks with cal-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. 1), 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. 1) 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 granitic melts in the uppermost crust (e.g., Bickford et al., 1986). 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 accommodated the southward growth of the USA Midcontinent.

Superimposed on the granite-rhyolite terrane is a large area underlain by a thick sub-Mt. Simon (i.e., ?late Precambrian) sedimentary basin centered around western Ohio, northeastern Kentucky, and southern Indiana immediately to the east of the study area ("Middle Run Formation" (Shrake et al., 1991; Drahovzal and Harris, 1992; Wickstrom et al., 1992). The actual age of this arkosic sandstone is unknown and could be early Cambrian to Proterozoic (Wolfe et al., 1993).

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 strata. Maps of the distribution of the layered reflectivity in the shallow uppermost crust (e.g., Fig. 2) were first produced by McBride and Kolata (1999) and McBride et al. (2003), based on original and reprocessed industry seismic reflection data from the central part of the basin. On the basis of the geometry and internal structure, and seismic stratigraphy of the shallow layered reflectivity, they suggest a late Proterozoic rift basin or collapsed caldera complex for the local origin of the granite-rhyolite province underlying the central Illinois basin. In such case, the province could be a result of the intrusion/extrusion of material following decompression melting in the lithosphere associated with rifting and extension.

Although other geophysical information on the Precambrian crust below the Illinois basin is somewhat limited, sufficient exists to characterize the velocity structure of the crust and uppermost mantle, as well as regional crustal thickness for the study area (e.g., see compilation by Braile (1989) and Heigold (1991)). Regional seismic refraction data have been used to obtain one-dimensional and two-dimensional velocity-depth models of the crust, which are available for converting reflection travel times to depth (Braile et al., 1981; Ginzburg et al., 1983; Braile, 1989; Catchings, 1999). The results of two seismic refraction profiles 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), and a contour map of crustal thickness for the central USA has been presented by Braile (1989). From an east-west refraction profile across the southern margin of the study area (Fig. 1), 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, which are comparable to values derived for the upper and middle crust from refraction profiles for the northern Mississippi embayment to the south (6.20 km/s 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, which is consistent with more recent compilation maps 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, 1999; W. D. Mooney, 2000, written communication). 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 provides a model where crustal velocities and crustal thickness are greater than for our study area (Catchings, 1999); however, as shown by the compilation by Braile (1989), 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. 1). We note that Catchings (1999)'s north-south velocity model shows a flat mantle refractor just above 60 km depth.

Converting both of Braile et al. (1981)'s 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"). The seismic velocity for uppermost mantle within the area is given as 8.1 km/s in Braile et al. (1981). Although actual mantle xenolith samples are not available for the study area, Helffrich and

Wood (2001) observed that peridotites appear to be the dominant rock type of the mantle with a typical seismic velocity of about 8.2 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). 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 ever described (Pratt et al., 1989).

Methodology

Reprocessing of several hundred kilometers of industry seismic reflection data using extended vibroseis correlation was performed. The original industry reflection profiles were acquired along three regional lines (Fig. 2, 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 per 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 first the highest frequencies followed by gradually lower frequency components (Fig. 3). 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 travel time. 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 (Figures 3, 4, 5, and 6). Thus, the frequency content of the recorrelated data for expected lower crust-uppermost mantle traveltimes (e.g., 10-16 s; Fig. 6) mimicked that for the previous COCORP deep seismic reflection program (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.

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 per cent of the 2-D 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. We present the results of the reprocessing as interpretive 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. The deeper results are presented as unmigrated in order to mitigate possible overmigration 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. The description and interpretation of upper crustal reflector structure are presented elsewhere (McBride and Kolata, 1999; McBride et al., 2003).

Results and Interpretation

Our observations from the reprocessing results are grouped as (a) upper crustal reflectivity (0-7 s), (b) lower crustal reflectivity and the Moho discontinuity (7-12 s), and (c) uppermost mantle reflectivity (12-~20 s). Figures 7, 8 and 9 are line drawings of the reprocessed seismic profiles S-1, S-2 and S-3, respectively, from 0 to 20 s. In our two-dimensional mapping of reflectors, we incorporated the COCORP profiles where appropriate. In general, the results of the new reprocessing of the records for the 10-20 s interval are successful. The quality of images of lower crustal reflectivity and the Moho exceeds that of the COCORP profiles from the area. The reprocessed profiles show intermittent but clear images of lower crustal reflections and diffractions, the Moho, and sub-Moho and upper mantle reflections.

Upper crustal reflectivity

Distinct nearly horizontal reflectors define the uppermost sedimentary units of the crust 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 seismic stratigraphic sequences ("Centralia sequence") using 10 s (~30 km) record sections. In their study, they noted that beneath the Paleozoic strata of the Illinois basin, deeper Proterozoic reflectivity is complex and highly structured and appears to be embedded in or part of (or both) 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 (Figures 7 and 8). The geometry of reflections in some places strongly suggests stratiform unconformity-bounded deposits that could be interpreted as seismic stratigraphic sequences of sedimentary and/or volcaniclastic layers.

Pratt et al. (1992) originally described the "Centralia sequence" as a hypothetical Proterozoic sedimentary basin based on the Illinois and Indiana COCORP profiles (Fig. 2). Based on a loose network of industry seismic profiles, McBride and Kolata (1999) and McBride et al. (2003) subsequently subdivided Precambrian reflectivity into three prominent sequences A, B and C as shown in Fig. 7, and produced iso-traveltime structural contour maps. The Enterprise subsequence is a distinct bowl-shaped succession of reflective units in the upper part of the Centralia sequence immediately beneath the Cambrian Mt. Simon Sandstone with distinct pinch-out boundaries (Figures 7, 8 and 9). McBride et al. (2003) suggested that this subsequence consists of unconformity-bound depositional units.

Lower crustal reflectivity and the Moho

Lower crustal reflectors (7-12 s) appear as intermittent horizontal packages and short gently dipping reflections and diffractions. 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 short reflection segments dominate much of the section. Upon migration, the diffractive zones collapse into discontinuous “pods” of segmented or dipping reflectors.

A series of horizontal reflectors appears between 11.3 and 11.6 s (~37 km depth) on profile S-2 near the intersection of S-1 (Fig. 10). The crustal section immediately above this level is marked by complex reflector geometries including dipping reflections that are truncated by the deeper horizontal reflections. Increasing the migration velocity resolves partly collapsed diffractions into sub-horizontal and dipping reflections (Fig. 11). Below about 11.6 s, the section is remarkably blank except for deeper dipping events, discussed below. This vertical division in reflectivity is also observed on the eastern end of the profile, at the same traveltime at which a gradual vertical cessation of reflectivity is observed (Fig. 11). The lower crustal reflection pattern on S-1 matches that of S-2. On line S-1 prominent horizontal to sub-horizontal reflectors appear at ~ 11.5 s, especially beneath the middle of the profile. These reflectors also mark a division between complex lower crustal reflectivity and a greatly reduced reflectivity below, except for prominent isolated, individual reflection packages at a much greater traveltime. On profile S-3, limited intermittent horizontal reflections appear within the 11.5-12.5 s interval (Fig. 12). As on the previous two profiles, this interval marks a boundary between crustal reflectivity and blank or prominent dipping reflections below.

The arrival time for the horizontal reflectivity or boundary between reflective and poorly reflective section corresponds to the Moho discontinuity as defined from modeling of local seismic refraction profiles and regional crustal thickness compilations as described above. We thus interpret this reflectivity boundary as the Moho, which corresponds to depths of 37-39 km. The Moho as observed on the S profiles is typically defined worldwide by the limit of lower crustal subhorizontal reflectivity (e.g., Klemperer et al., 1986; Prussen, 1991; BABEL Working Group, 1993). 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 for example 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 with no amplitude correction or deconvolution processing (e.g., Fig. 4) typically show a strong decay to 6-7 s, followed by a gently sloping or flat curve to the bottom of the record; however, the decay is frequently 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 et al., 1989), which orthogonally intersects S-1, a base of crustal reflectivity is not usually clearly 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, and so is deemed incorrect. 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 applied to the industry data, in order to compare the two data sets (Fig. 13). Although the reprocessed industry data are better quality and 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. 13) 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.

Upper most mantle reflectivity

Migrated reflections observed beyond the Moho arrival time of 12 s (see migrated data excerpts, Figures 11, 15, and 16) are considered mantle features. 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). In the profiles mantle reflectors appear as discrete, isolated gently dipping events before and after migration. They appear beneath zones of comparatively significant lower crustal reflectivity in some cases, even seeming to materialize within "columns" of higher signal-noise ratio due perhaps to localized zones of greater signal penetration. The "column" effect is especially noticeable on line S-2 (Fig. 10), and where the lateral extent of a mantle reflector is interrupted by a "column" of poor coherency (e.g., line S-1, Fig. 14), a greater lateral extent is implied. We note that this effect is also observed on the COCORP Illinois profiles, although with much greater severity (Pratt et al., 1992). However, other than this relationship, the mantle reflectors cannot usually be directly correlated with lower crustal structural trends. Because, for the most part, reflector attitude in the lower crust is irregular, correlation with mantle reflectors is difficult.

As seen from true amplitude decay curves, integrated for the region of the mantle reflectivity on line S-1 (Fig. 4), amplitude levels for returning signal from the mantle is equivalent to that from the Moho reflection. Frequency spectra (Fig. 6) show peak values of 21-34 Hz at 14-16 s in the mantle, which is within the expected frequency based on the theoretical recorrelation bandwidth of 14 Hz to ~42 Hz at 16 s (Fig. 5). A 21-34 Hz signal would provide a favorable vertical resolution limit 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 km 82.5, just north of line S2 (Fig. 7 and 15). This reflection group has a horizontal length of 16.5 km and gentle apparent dip of about 20^o towards the south (unmigrated). Using a simple “straight-ray” migration, the migrated apparent dip would be expected to be $1\text{-}2^o$ steeper. Further south along the profile a less prominent reflection group (“b”) comes in at 16.45 s (56.34 km depth) and is collinear with “a” and thus is likely a southward extension of it. Still further south, a third short almost collinear reflection segment (“c”) occurs at 14.5 s (48.4 km depth) below km 47. As stated above, lower crustal reflectivity appears more intense above these mantle reflectors but does not show any clear correlation with any of them.

On the southernmost east-west line S-2, a 5.5-km long subhorizontal mantle event (“d”) is seen at approximately 14.75 s (49.4 km depth) below km 87 (Figures 8 and 11). 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 similar, but less well resolved feature at about the same travel time. A series of short, but distinct, planar mantle reflections appears further east at “e”, extending from 15.5 s to 17 s (km 53–59) just beneath the intersection of lines S-2 and S-1. This series dips apparently 16^o west and extends for a length of 10.6 km and is collinear with a deeper set of reflections arriving beneath km 65 to the west. This series correlates in time exactly with the lengthier south-dipping reflections observed from S-1 and thus provides corroboration as well as invaluable cross-line control for strike and dip. The mantle reflector image on S-2 is more complex and consists of four or five distinct, mostly west-dipping, segments. On both orthogonal profiles, the mantle reflector appears as an isolated feature, surrounded by a mostly reflection-free section, and does not continue up to the Moho. Because the reflectors correlate on intersecting profiles and behave in a stable manner upon seismic migration (Fig. 11), it is clear that they are not arriving significantly from out of the plane of section.

Along profile S-3, prominent mantle reflectivity is observed, but at lesser travel time. This is expected since the longest mantle reflector sequence on the north-south line S1 is dipping to the south along the line of profile. Here reflectors appear just beneath the Moho, centered below km 52 and dip more steeply into the mantle. In this instance, the attitude of lower crustal reflectivity matches somewhat (i.e., is collinear) with mantle features on the migrated records (Figures 9 and 16). The prominent mantle reflector 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 reflector 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^{o} west. Where the S-3 reflector sequence projects toward the intersection with S-1, a few poorly resolved south-dipping reflections project away on S-1. Because the S-3 sub-Moho is so close in time to the Moho level of 12.0-12.5 s, 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. 17). As can be seen from this exercise, crustal events (the Moho and a diffraction pattern, Fig. 17) 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 below the Moho level.

The correlation of unmigrated reflections across intersecting profiles enabled the computation of true dip and strike. This not only corroborates our observations, but provides the first case of obtaining an attitude for a mantle reflector for deep seismic reflection profiles in the USA. The true dip estimate is derived using apparent dips and gives a value of 24^{o} true dip, in the direction S 42^{o} W (222^{o}), and strikes NW-SE.

Discussion

Considering the rarity of mantle reflections on dedicated deep seismic reflection profiles in the United States (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 seismic data are infrequent, especially in the United States, where thousands of kilometers of dedicated deep reflection data 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 reflectors beneath the Illinois basin may be related to the unusually high Lg coda Q in the central Midcontinent (Baqer and Mitchell, 1998; Mitchell and Jemberie, 2001) or to the superior imaging related to the relatively broad frequency band (14-126 Hz) vibroseis and long-record (20 s) source. A high Lg coda Q corresponds to low attenuation of sound wave signals and consequently, higher quality image resolution and data. Lg coda Q values (at 1 Hz) 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. 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 reflectors could thus exist in other parts of the continental lithosphere of the USA where deep seismic reflection profiles have been surveyed, but cannot easily be imaged by seismic reflection method due to high levels of signal attenuation.

The mantle reflections, which appear as isolated events in an otherwise non-reflective uppermost mantle, cannot be uniquely correlated to any particular geologic feature in the Paleozoic basin or in the crust as observed from the new seismic sections. Therefore, reaching a unique interpretation is difficult. A similar ambiguity exists for strong mantle reflectors 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 for the Illinois basin, we must rely on limited drillhole-derived information on the underlying Proterozoic rocks in order to provide some constraints for interpreting the origin of 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 plate tectonic processes that may preserve reflector structure within mantle lithosphere. We also rely on better constrained analogs for mantle reflector interpretations from the North Sea, western Canada and the Baltic Sea (Cook and Vasudevan, 2003; Snyder and Flack, 1990; BABEL Working Group, 1993)

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. For the well-studied “Flannan” and “W” mantle reflectors beneath the West Orkney basin north of Scotland, Warner et al. (1996) suggested that the geometry, modeled physical properties, and geologic setting of the reflectors indicate fragments of eclogitized oceanic crust. The mantle reflectors are thus relicts of a pre-Caledonian (a Silurian orogeny affecting northwest Europe and eastern North America) 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 affecting the upper mantle (e.g., ductile shear zones). Beneath the northern Baltic Shield near the Proterozoic-Archean boundary (BABEL Working Group, 1990), dipping mantle reflectors can be traced upward to the Moho discontinuity or into the lowermost crust and are interpreted to represent relict Precambrian subduction zone surfaces.

Constraints from Basement Geology for the USA Midcontinent

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 (“Transcontinental Proterozoic province”, (Fig. 1), which consists mainly of epizonal to mesozonal (shallow to mid crustal depth intrusive) granite and related rhyolite that were extruded on and emplaced within the older Proterozoic rocks. These felsic igneous rocks have A-type (anorogenic) chemical affinities and accumulated in a within-plate tectonic environment, part of a mid-Proterozoic supercontinent at 1.5 Ga. The Felsic rocks are associated with subordinate within-plate tholeiitic basalt, which is taken to imply magmatism associated with crustal extension in mid-Proterozoic time, or as magmatism associated with some Proterozoic "hot spot" which would account for their vast occurrence. All of the rocks are essentially unmetamorphosed, and none are penetratively deformed.

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. 1). This isotopically defined boundary thus represents a Proterozoic continental margin situated just north of our region of mapped mantle reflectivity (Fig. 1). 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 southeastern border of the Archean and older Proterozoic provinces of Laurentia, as defined by Van der Lee (2001), lies generally north of the study area.

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. For the subduction scenario, 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. The reflectivity of such shear surfaces could result from alteration of existing rock due to heating and fluid activity associated with frictional sliding along the boundary. Proterozoic reconstructions described by Van Schmus et al. (1996) and Schneider et al. (2004) for the USA Midcontinent are suggestive of northwestward subduction. For a subduction zone hypothesis, our observations of a mantle reflector dipping to the southwest would imply localized complexity along the ancient continental margin beneath the present-day Illinois basin or a local reversal in subduction zone polarity. As pointed out above, an obvious problem with the subduction zone hypothesis for the felsic rocks beneath the area is the lack of deformation or metamorphism.

An alternative (Knapp et al., 2005) to the subduction hypothesis for the study area is lithospheric delamination, 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 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. The expected consequences of delamination to the overlying crust are rapid uplift and extension and rapid heating of the lower crust. Heating is 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 lead to the intrusion/extrusion of the granites and rhyolites beneath the Illinois basin derived from partial melts due to relative buoyancy.

Block and Royden (1990) and Bird (1991) postulated that in some regions wholesale flow of the lower crust has occurred on a geologically short time scale, a process usually associated with delamination. They further noted that flow of lower crustal material (lower crustal flow), as a process, can be explained as a consequence of decompression melting following delamination. The absence of crustal roots beneath old collision orogens and the presence of a sharp regionally flat Moho, as observed on deep seismic profiles worldwide (Allmendinger et al., 1987; Klemperer and Matthews, 1987; Bois, 1991; Cook et al., 1992) including our reprocessed seismic profiles, can also be considered as suggestive of lower crustal flow, and ultimately, delamination. On deep reflection profiles in general and for our case, the Moho beneath ancient collisional orogens is typically sharp, flat and from a structural point of view, "late" in sequence in that it either crosscuts dipping reflectors in the overlying crust or it acts as a decollement for overlying dipping reflectors (Cook et al., 1992; Cook and Varsek, 1994).

The concept of delamination and associated lower crustal flow provides an alternative to Precambrian subduction for the occurrence of dipping reflectors in the mantle beneath the Illinois basin. In this interpretation, the mantle reflectors could represent either "scars" of delamination in the form of intact pieces of former lower crust that has been partially detached from the lower crust or the remains of slab imbrication as shown, for example, by Cook et al. (1998) for western Canada.

Relation of Mantle Reflectivity to Illinois Basin (and Proto-Basin?)

The anomalous mantle reflectivity is localized directly beneath the deepest part of the Illinois basin north of the Reelfoot rift (Fig. 1) as well as directly beneath the Cambrian Mt. Simon depocenter and the ?Proterozoic Enterprise Sequence (Fig. 18) and underlying interpreted Proterozoic seismic stratigraphic sequences ("Enterprise Subsequence") (McBride and Kolata, 1999; McBride et al., 2003) (Figures 7, 8, and 9). It therefore seems reasonable to 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 that influenced subsidence of the basin. 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. Superposing the contours of the basal Cambrian unit of the Illinois basin and deeper sequences on the mantle reflector contours (Fig. 18) shows a limited degree of parallelism.

The fact that the mantle reflector pattern observed for our study 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 precursors structures. McBride et al. (2003) proposed that the upper crustal Proterozoic seismic 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. 18), after which subsidence shifted to the south over the Reelfoot rift (Fig. 1). We suggest in like manner that the mantle reflector pattern may have played an analogous role; however, the actual controlling mechanism is not clear.

Baird et al. (1995) previously documented a case of dipping reflectors beneath the northern Williston basin in Montana and North Dakota from COCORP deep seismic reflection profiles interpreted as mantle in origin although no Moho reflection was identified. The Williston basin is in many ways closely 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 reflectors represent a preserved crustal root of previous Precambrian collisional orogeny (Hudsonian), now preserved as remnant crustal "keel" underwent eclogite-facies metamorphism, which then overprinted the base of a 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).

Other instances of sub-Moho mantle reflectors beneath sedimentary basins have been described in terms of deformational structures that accommodated basin extension and subsidence (e.g., North Sea, Klemperer and White, 1989; Flack et al., 1990). Klemperer and White (1989) used deep seismic reflection data from the North Sea rift in order to show that mantle reflector patterns mimicked crustal features associated with rifting. Mantle reflectors were found to lie symmetrically beneath the margins of the rift, which was interpreted to represent coaxial stretching of the crust facilitated by shearing in the uppermost mantle. For our study, such a broad perspective for the Illinois basin and the surrounding Midcontinent is not available from deep seismic reflection profiles; however, we can conclude that no other instances of dipping mantle reflectors have been observed on profiles in areas adjacent to the basin in Illinois, Indiana, Missouri, and Arkansas (Pratt et al., 1989). Thus we cannot yet see evidence for interpreting our results as part of a symmetric system of mantle reflectivity beneath the Illinois basin.

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 “spec data” seismic reflection data were transformed into deep seismic profiles penetrating as deep as the upper part of the Earth’s mantle. Beneath the mostly undeformed Paleozoic sedimentary sequences of the Illinois basin lie layered Proterozoic basements rocks that appear to have formed as either a Proterozoic sedimentary basin or as tabular intrusive bodies or both. 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 on the attitude of those observed in this study, lithospheric plate subduction is proposed for one possible origin. This could have resulted from geodynamic processes associated with terrane collision in Proterozoic time. The occurrence of granites and rhyolites (A-type) 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 immediately north of the study area. However certain anticipated subduction related evidence is not seen, such as metamorphosed rock complexes (mélange) and associated deformation structures.

An alternative process involving lithospheric delamination of the mantle lithosphere resulting from Proterozoic terrane collision and accretion is more consistent with observed data because actual structural effects anticipated from such process can be seen. 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 sharp, flat Moho and the absence of crustal roots beneath the present-day Illinois basin are suggestive of crustal flow, a process resulting from delamination.

Finally, the mantle structure trends suggest some control on processes leading to the development of overlying younger features in the region. Depth contours for mantle structures, Proterozoic basement rock sequences and Paleozoic basin strata all fall within the same location and correlate considerably well suggesting structural relation between them.

References

Aberg, G. 1988, Middle Proterozoic anorogenic magmatism in Sweden at worldwide: Lithosphere, v. 21, p. 279-289.

Akinci, A., Herrmann, R. B., Ammon, C. J., 1999, Upper-crustal structure in the Mississippi Embayment and adjacent areas form teleseismic receiver analysis (abstract): SSA-99 94th Annual Meeting Abstracts, Seismological Research Letters, v. 70, Issue 2, p. 274.

Allmendinger, R., Hauge, T., Hauser, E., Potter, C., Klemperer, S., Nelson, K., Knuepfer, P., and Oliver, J., 1987, Overview of the COCORP 40°N transect, western United States: The fabric of an orogenic belt: Geological Society of American Bulletin, v. 98, p. 308-319.

BABEL Working Group, 1990, Evidence for early Proterozoic plate tectonics from seismic reflection profiles in the Baltic shield: Nature, v. 348, p. 34-38.

BABEL Working Group, 1991, Deep seismic surveys images crustal structure of Tornquist Zone beneath southern Baltic Sea: Geophysical Research Letters, v. 18, p. 1091-1094.

BABEL Working Group, 1993, Integrated seismic studies of the Baltic shield using data in the Gulf of Bosnia region: Geophysical Journal International, v. 112, p. 305-324.

Baird, D. J., Knapp, J. H., Steer, D. N., Brown, L. D., and Nelson, K. D., 1995, Upper mantle reflectivity beneath the Williston basin, phase-change Moho, and the origin of intracratonic basins: Geology, v. 23, no. 5, p. 431-443.

Baqer, S., and Mitchell, B.J., 1998, Regional variation of Lg Coda quality in the Continental United States and its Relation to Crustal Structure and Evolution: Pure and Applied Geophysics, v. 153, p. 613-638.

Best, J.A., 1990, The nature of upper mantle reflectivity beneath the Montana plains on COCORP seismic reflection data from amplitude and frequency decay curves: Eos, Transactions, American Geophysical Union, v. 71, p. 561.

Bickford, M. E., Van Schmus, W. R., and Zietz, I., 1986, Proterozoic history of the midcontinent region of North America: Geology, v. 14, p. 492-496.

Bird, P., 1979, Continental delamination and the Colorado Plateau: Journal of Geophysical Research, v. 84 (B13), p. 7561-7571.

Bird, P., 1991, Permo-Triassic succession of the Kekneno area, West Timor: implications for paleogeography and basin evolution: Journal of Southeast Asian Earth Sciences, v. 6, iss. 3-4, p. 359-371.

Block, L., and Royden, L. H., 1990, Core complex geometries and regional scale flow in the lower crust: Tectonics, v. 9, p. 557-568.

Bois, C., 1991, Geological significance of seismic reflection in collision belts: Geophysical Journal International, v. 105, p. 55-69.

Bowring, S. A., Arvidson, R. A., and Podosek, F. A., 1988, The Missouri gravity low; evidence for a cryptic suture?: Geological Society of America Abstracts with programs, v. 20, no. 2, p. 91.

Bowring, S.A., Housh, T.B., and Podosek, F.A., 1991, Nd isotopic constraints on the evolution of Precambrian ‘anorogenic’ granites from Missouri: Eos Transactions American Geophysical Union, v. 72, issue 17, p. 310.

Braile, L.W., 1989, Crustal structure of the continental interior *in* Pakiser, L.C., Mooney, W. D., eds., Geophysical framework of the continental United States: Geological Society of America Memoir, v. 172, p. 285-315.

Braile, L. W., Hinze, W. J., Sexton, J. L., Keller, G. R., Lidiak, E. G., 1981, An integrated geophysical and geological study of the tectonic frame work of the 38th parallel lineament in the vicinity of its intersection with the extension of the New Madrid fault zone: Annual Program Report to the US Regulatory committee (NUREG/CR-1878), p. 131.

Brown, L.D., and seven others, 1983, Intracrustal complexity in the United States midcontinent; Preliminary results from COCORP surveys in northeastern Kansas: Geology, v. 11, p. 25-30.

Buschbach, T. C., and Kolata, D. R., 1990, Regional setting of Illinois Basin, *in* Leighton, M. W., Kolata, D. R., Oltz, D.F., and Eidel, J. J., eds., Interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 29-55.

Catchings, R. D., 1999, Regional Vp, Vs, Vp/Vs and Poisson’s ratio across earthquake source zones from Memphis, Tennessee to St. Louis, Missouri: Bulletin of the Seismological Society of America, v. 89, p. 1591-1605.

Chulick, G.S., and Mooney, W.D., 1999, Crustal structure of North America and the adjacent ocean

Basins: a new synthesis: Eos Transactions American Geophysical Union, v. 80, iss. 46, p. 711.

Cook, F. A., and nine others, 1992, Lithoprobe crustal reflection cross section of the south Canadian Cordillera 1: Foreland thrust and fold belt to Frazier River Fault: Tectonics, v. 11, p. 12-36.

Cook, F.A. and Varsek, J.L., 1994, Orogen-scale decollements: Reviews of Geophysics, v. 32, issue 1, p. 37-60.

Cook, F. A., and Vasudevan, K., 2003, Are there relict crustal fragments beneath the Moho?: Tectonics, v. 22, no. 3, p. 1026.

Cook, F.A., van der Velden, A.J., Hall, K.W., Roberts, B.J., 1998, Tectonic delamination of the Precambrian lithosphere in northwestern Canada mapped by LITHOPROBE: Lithoprobe Report, no. 64, p. 54-69.

Cook, F.A., van der Velden, A.J., Hall, K.W., Roberts, B.J., 1999, Frozen subduction in Canada's Northwest Territories: Lithoprobe deep lithospheric reflection profile of the western Canadian shield: Tectonics, v. 18, iss. 1, p. 1-24.

Drahovzal, J.A., 1997, Proterozoic sequences and their implications for Precambrian and Cambrian geologic evolution of western Kentucky: evidence from seismic reflection data: Seismological Society of America, v. 68, p. 553-566.

Drahovzal, J. A., Harris, D. C., 1992, *in* Wickstrom, L.H., Walker, D., Baranoski, M. T., Keith, B., Furer, L. C., eds., The East Continent Rift Basin: A New Discovery Special Publication Kentucky Geological Survey, Report No. 18, series X1, p. 25.

Flack, C. A., Klemperer, S. L., McGeary, S. E., Snyder, D. B., and Warner, M. R., 1990, Reflections from mantle fault zones around the British Isles: Geology, v. 18, p. 528-532.

Ginzburg, A., Mooney, W. D., Walter, A. W., Lutter, W. J., and Healy, J. H., 1983, Deep structure of north Mississippi embayment: American Association of Petroleum Geologists Bulletin., v. 67, p. 2031-2046.

Goetz, L. K., Tyler, J. G., Macarevich, R. L., Brewster, D., and Sonnad, J. R., 1992, Deep Gas Play probed along Rough Creek graben in Kentucky part of southern Illinois Basin: Oil and Gas Journal, v. 90, p. 97-101.

Hamdani, Y., Mareschal, J., and Arkani-Hamed, J., 1994, Phase change and thermal subsidence of the

Williston Basin: Geophysical Journal International, v. 116, issue 3, p. 585-597.

Heigold, P.C., 1991, Crustal character of the Illinois Basin, *in* Leighton, M.W., Kolata, D.R., Oltz, D.F., and Eidel, J.J., eds., Interior Cratonic Basins: American Association of Petroleum Geologists Memoir 51, p. 247-261.

Helffrich, G.R., and Wood, B.J., 2001, The Earth's mantle: Nature, v. 412, p. 501-507.

Hoffman, P. F., 1989b, Speculations on Laurentia's first gigayear (2.0 to 1.0 Ga): Geology, v. 17, p. 135-138.

Karlstrom, K. E., Harlan, S. S., Williams, M. L., McLelland, J., Geissman, J. W., and Ahall, K. I., 1999, Refining Rodinia; geologic evidence for the Australia - western U.S. connection in the Proterozoic: GSA Today, v. 9 (10), p. 1-7.

Kay, R.W., and Kay, S.M., 1993, Delamination and delamination magmatism: Tectonophysics, v. 219, issue 1-3, p. 177-189.

Klemperer, S.L., Hauge, T.A., Hauser, E.C., Oliver, J.E., and Potter, C.J., 1986, The Moho in the northern Basin and Range Province, Nevada, along the COCORP 40 degrees N seismic reflection transect: Geological Society of America, v. 97, iss. 5, p. 603-618.

Klemperer, S. L., and Matthews, D. H., 1987, Iapetus suture located beneath the North Sea by BIRPS deep seismic reflection profiling: Geology, v. 15, p. 195-198.

Klemperer, S. L., and White, N., 1989, Coaxial stretching or Lithosphere simple shear in the North Sea? Evidence from deep seismic profiling and subsidence: America Association of Petroleum Geologists Memoir 46, Extensional Tectonics and stratigraphy of the North Atlantic margins.

Knapp, J.H., Knapp, C.C., Raileanu, V., Matenco, L., Mocanu, V., and Ding, C., 2005, Crustal constraints on the origin of mantle seismicity in the Vrancea Zone, Romania: the case for active continental lithospheric delamination: Tectonophysics, in press.

Knapp, J.H., and ten others, 1996, Lithosphere-scale seismic image of the Southern Urals form explosion source reflection profiling: Science, v. 274, iss. 5285, p. 226-228.

Kolata, D.R., 1991, Overview of sequences, *in* Leighton, M.W., Kolata, D.R., Oltz, D.F., Eidel,J.J., eds., Interior Cratonic Basins: American Association of Petroleum Geologists Memoir 51, p. 59-73.

Leighton, M.W., and Kolata, D.R., 1991, Selected Interior Cratonic Basins and Their Place in the Scheme of Global Tectonics: A Synthesis, Interior Cratonic Basins: American Association of Petroleum Geologists Memoir 51, p. 729-797.

Lidiak, E.G., 1996, Geochemistry of subsurface Proterozoic rocks in the eastern Midcontinent of the United States: further evidence for a within-plate tectonic setting *in* van der Pluijm, B. A., Catacosinos, P. A., eds., Basement and Basins of Eastern North America: Geological Society of America Special Paper, v. 308, p. 45-66.

McBride, J. H., and Kolata, D. R., 1999, Upper crust beneath the central Illinois basin, United States: Geological Society of America Bulletin, v. 111, no. 3, p. 375-394.

McBride, J. H., Nelson, W. J., and Marshak, S., 2003, Phanerozoic strike slip faulting in the continental interior platform of the United States; examples from the Laramide orogen, mid continent and ancestral Rocky Mountains: Geological Society of London Special Publications, v. 210, p. 159-184.

McBride, J.H., Snyder, D.B., Tate, M.P., England, R.W., and Hobbs, R.W., 1995, Upper mantle reflector structure and origin beneath the Scottish Caledonides: Tectonics, v. 14, iss. 6, p. 1351-1367.

McGeary, S., and Warner, M.R., 1985, Seismic profiling of the continental Lithosphere: Nature, v. 317, p. 795-797.

Melhuish, a., Holbrook, W. S., Davey, F., Okaya, D.A., and Stern, T., 2004, Crustal and upper mantle structure of the Australian Plate, South Island, New Zealand: Tectonophysics, v. 395, p. 113-135.

Menuge, J., Brewer, T., and Seeger, C., 2002, Petrogenesis of metaluminous A-type rhyolites from the St. Francois Mountains, Missouri and the Mesoproterozoic evolution of the southern Laurentian margin: Precambrian Research, v. 113, p. 269-291.

Mitchell, B.J., and Jemberie, A.L., 2001, Seismic Q and evolution of the continental crust: Abstracts with Programs-Geological Society of America, v. 33, issue 6, p. 240.

Mooney, W.D., 2000, The origin of continental crust; seismic constraints: Eos Transactions American Geophysical Union, v. 81, issue 48, p. 1269.

Mooney, W.D., Braile, L.W., 1989, The seismic structure of the continental crust and upper mantle of North America, *in* Bally, A.W., Palmer, A.R., eds., The Geology of North America: an Overview: Geological Society of America, Boulder, Co, Publishers.

Nelson, K.D., 1992, Are crustal thickness variations in old mountain belts like the Appalachians a consequence of lithospheric delamination?: Geology, v. 20, p. 498-502.

Nelson, K.D., 1991, A unified view of cratonic evolution motivated by recent seismic reflection and refraction results: Geophysical Journal International, v. 105 (1), p. 25-35.

Nelson, K.D., and DePaolo, D.J., 1985, Rapid production of continental crust 1.7-1.9 b.y. ago: Nd isotopic evidence from the basement of the North American Midcontinent: Geological Society of America Bulletin, v. 96, p. 746-754.

Okaya, D. A., and Jarchow, C. M., 1989, Extraction of deep crustal reflections from shallow Vibroseis data using extended correlation: Geophysics, v. 54, p. 555-562.

Potter, C.J., Drahovzal, J.A., Sargent, M.L., and McBride, J.H., 1997, Proterozoic structure, Cambrian rifting, and younger faulting as revealed by a regional seismic reflection network in the southern Illinois Basin: Seismological Society of America, v. 68, iss. 4, p. 537-552.

Pratt, T., Culotta, R. C., Hauser, E., Nelson, D., Brown, L., Kaufman, S., Oliver, J., and Hinze, W., 1989, Major Proterozoic basement features of the eastern Midcontinent of North America revealed by recent COCORP profiling: Geology, v. 17, p. 505-509.

Pratt, T.L., Hauser, E.C., Nelson, K.D., 1992, Wide spread buried Precambrian layered sequences in the U.S. mid-continent: Mid-continent evidence for large Proterozoic depositional basins: American Association of Petroleum Geologists Bulletin, v. 76, p. 1384-1401.

Prussen, E.I., 1991, The reflection Moho along the northwest USA transect: Eos Transactions American Geophysical Union, v. 22, p. 315-322.

Reston, T.J., 1990, Mantle Shear Zones and the Evolution of the North Sea Basin: Geology, v. 18, p. 272-275.

Rivers, T., and Corrigan, D., 2000, Convergent margin on southeastern Laurentia during the Mesoproterozoic; Tectonic implications: Canadian Journal of Earth Sciences, v. 37, p. 359-383.

Sacks, P.E., and Secor, D.T., 1990, Delamination in collisional orogens: Geology Boulder, v. 18, issue 10, p. 999-1002.

Schneider, D.A., Holm, D.K., and Van Schmus, W.R., 2004, Accretion growth and stabilization of

Laurentide Crust; and example from the Proterozoic Mid-continent of North America (Abstract) in Hatcher, R.D., Jr., Editor, 4-D Framework of the Continental Crust-Integrating Crustal Process Through Time, 17th International basement Tectonics Conference, Knoxville, Tenn., USA, Programs with Abstracts, p. 50-51.

Schwalb, H.R., 1969, Deep-(Cambro-Ordovician) exploration in western Kentucky: Kentucky Geological Survey, Kentucky Oil and Gas Association 32nd Annual Meeting, p. 16-19.

Serpa, L.F., and seven others, 1984, Structure of the southern Keweenawan rift from COCORP surveys across the Midcontinent geophysical anomaly in northeastern Kansas: Tectonics, v. 3, issue 3, p. 367-384.

Shrake, D.L., Carlton, R.W., Wickstrom, L.H., Potter, P.E., Richard, B.H., Wolfe, P.J., and Sitler, G.M., 1991, Pre-Mount Simon Basin under the Cincinnati Arch: Geology, v. 19, p. 139-142.

Shuster, R.D., 2001, Models for the origin of the Mesoproterozoic “granite-rhyolite” province: Geological Society of America Abstract with Programs, v. 33, no. 4, p. 10.

Steer, D.N., Knapp, J.H., and Brown, L.D., 1998, Super-deep reflection profiling: exploring the continental mantle lid: Tectonophysics, v. 286, iss. 1-4, p. 111-121.

Snyder, D. B., and Flack, C. A., 1990, A Caledonian age for reflectors within the mantle lithosphere north and west of Scotland: Tectonics, v. 9, no. 4, p. 903-922.

Snyder, D.B., England, R.W., and McBride, J.H., 1997, Linkage between mantle and crustal structures and its bearing on inherited structures in northwestern Scotland: Journal of the Geological Society of London, v. 154, p. 79-83.

Van der Lee, S., 2001, Deep below North America: Science, v. 294, p. 1297-1298.

Van Schmus, W.R., and Bickford, M.E., 1981, Proterozoic chronology and evolution of the midcontinent region, North America, *in* Kroner, A., ed., Precambrian plate tectonics: Elsevier, Amsterdam, p. 261-296.

Van Schmus, W.R., Bickford, M.E., and Turek, A., 1996, Proterozoic geology of the east-central Midcontinent basement *in* van der Pluijm, B.A., Catacosinos, P.A., eds., Basement and basins of eastern North America: Geological Society of America Special Paper, v. 308, p. 7-32.

Warner, M.R., 1990, Modeling of synthetic seismic reflection data: CCSS workshop 1987, data set V:

Paper-Geological Survey of Canada, p. 219-224.

Warner, M., Morgan, J., Barton, P., Morgan, P., Price, C., and Jones, K., 1996, Seismic reflections from the mantle represents relict subduction zones within the continental lithosphere: Geology, v. 24, no. 1, p. 39-42.

Wickstrom, L.H., Drahovzal, J.A., Keith, B.D., (coordinators), 1992, The geology and geophysics of the East Continent Rift Basin: Indiana Geological Survey Open-Files Study, Bloomington Indiana, OFS92/04, v. 103, p. 32 fig., 23 pl.

Windley, B.F., 1989, Anorogenic magmatism and the Grenvillian Orogeny: Canadian Journal of Earth Science, v. 26, p. 479-489.

Wolfe, P.J., Richard, B.H., and Potter, P.E., 1993, Potential seen in Middle Rub basins of western Ohio: Oil Gas Journal, p. 68-73.

Yilmaz, O., 1987, Seismic data processing: Society of Exploration Geophysicists, Tulsa, p. 526.

Figure captions

Figure 1. Index location map of the research area showing the primary geologic (basement) and tectonic boundaries of central USA. The thin dashed oval line represents the extent of the Illinois basin, while the asterisks symbol showing the location of the observed mantle reflectors. The light shaded region delimits the Eastern Granite Rhyolite Province (EGRP), while the dark 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 Nd isotope data in Van Schmus et al., (1996) while the thinner dashed line indicates the southeastern limit of the Laurentian continental margin as defined in van der Lee, (2001). GFTZ indicates the Grenville Front tectonic zone and SCPO is the southern Central Plains orogen.

Figure 2. Map of research area showing primary survey lines used for the study (S1, S2 & S3, bold straight red lines). IL, IN, and KY are the states of Illinois, Indiana and Kentucky respectively (solid black, curved line boundaries). IL-1, IL-2 and IN-1 are COCORP profiles. Dashed faint lines indicate county boundaries, while the dashed thick black line 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). The thick green bold contours represent mantle reflector attitude at depth corresponding to 14.5 s two-way travel time in the northeast to 17.5 s in the southwest while the dashed blue contours represent the base of the Precambrian “layered” rocks (Centralia sequence, McBride and Kolata, 1999) and illustrate the attitude of Proterozoic basement. Contour values are in seconds (two-way travel time).

Figure 3. Frequency time graph illustrating frequency bandwidth variation with extended recorrelation seismic data as opposed to conventional (4 second) correlation modified from Okaya and Jarchow, (1989).

Figure 4. Graph illustrating natural amplitude decay with travel time from average traces over area of prominent mantle reflector on N-S section, S-1. Amplitude changes indicate greater impedance contrast between media. Continued amplitude decay to bottom of record implies continued signal penetration.

Figure 5. Graph illustrating typical variation (decrease) in frequency bandwidth with travel time.

Figure 6. Frequency spectra illustration over mantle reflectivity indicating persistence of usable frequency content into the upper mantle. Vertical resolution at mantle velocity of approx. 100m is still possible below 14 seconds (vertical axis).

Figure 7. Line drawing of S-1 seismic reflection profile showing mantle reflectors a, b and c and crustal reflector trends (Crustal reflectivity description in McBride et al., 2003).

Figure 8. Line drawing of S-2 seismic reflection profile showing mantle reflectors d, e and f and crustal reflectors (Crustal reflectivity description in McBride et al., 2003).

Figure 9. Line drawing of S-3 seismic reflection profile showing mantle reflector g, and crustal reflectors (Crustal reflectivity description in McBride et al., 2003).

Figure 10. Excerpt section from seismic reflection profile S-2 illustrating mantle reflector “d” (unmigrated). Two-way travel times are in seconds (vertical axis) and correspond to depths between 45 and 55 km from the surface.

Figure 11. Excerpt section from seismic reflection profile S-2 illustrating mantle reflector intersection with that on S-1 profile (migrated). Two-way travel times are in seconds (vertical axis) and correspond to depths between 45 and 55 km from the surface.

Figure 12. Excerpt section from seismic reflection profile S-3 illustrating mantle reflector “g” (unmigrated). Vertical axis represents two-way travel time in seconds and arrow indicates reflection Moho time.

Figure 13. Excerpt section from COCORP IL-1 LINE seismic line profile illustrating “column effect” on data. Reflectors at 11.5 s travel time (vertical axis) indicate the reflection Moho. S-1 indicates the intersection of seismic line profile S-1 with the profile.

Figure 14. Top; Excerpt section from seismic reflection profile S-1 illustrating mantle reflector “a” (unmigrated). Two-way travel times in seconds (vertical axis) correspond to depths between 45 and 55 km from the surface. Bottom; Excerpt from profile S-1 showing mantle reflectors “a” and “b”, with coherency filter applied (courtesy of Arie van der Velden, University of Calgary) similar to the filters applied to Lithoprobe seismic data (e.g., Cook et al., (1999)). Horizontal line indicates the reflection Moho at 12 s.

Figure 15. Excerpt section from seismic reflection profile S-1 illustrating mantle reflector “a” (migrated). Two-way travel times in seconds (vertical axis) correspond to depths between 45 and 55 km from the surface.

Figure 16. Excerpt section from seismic reflection profile S-3 illustrating mantle reflector “g” (migrated). Vertical axis represents two-way travel time in seconds and the horizontal line indicates reflection Moho time.

Figure 17. Excerpts of seismic profile line 3 (migration spectra) illustrating effects of different velocity migrations on observed mantle reflectors.

Figure 18. Contours relation map illustrating the consistency between mantle reflector structural contours and those of the Proterozoic basement and Paleozoic Illinois basin when superimposed. The thick solid contours represent the mantle reflectors while the thin solid lines are contours to the base of the Proterozoic sequence. The dashed line contourings represent the attitude and extent of the base of the Paleozoic sequences of the Illinois basin.

Figure 19. Proterozoic continent reconstruction map illustrating the then location of the study just below the southeastern margin of the Laurentian continent. SGRP is the southern Granite-Rhyolite Province.

Figure 20. Model for lithospheric delamination in the Proterozoic. The future Illinois basin may have developed on the resulting accreted complex.

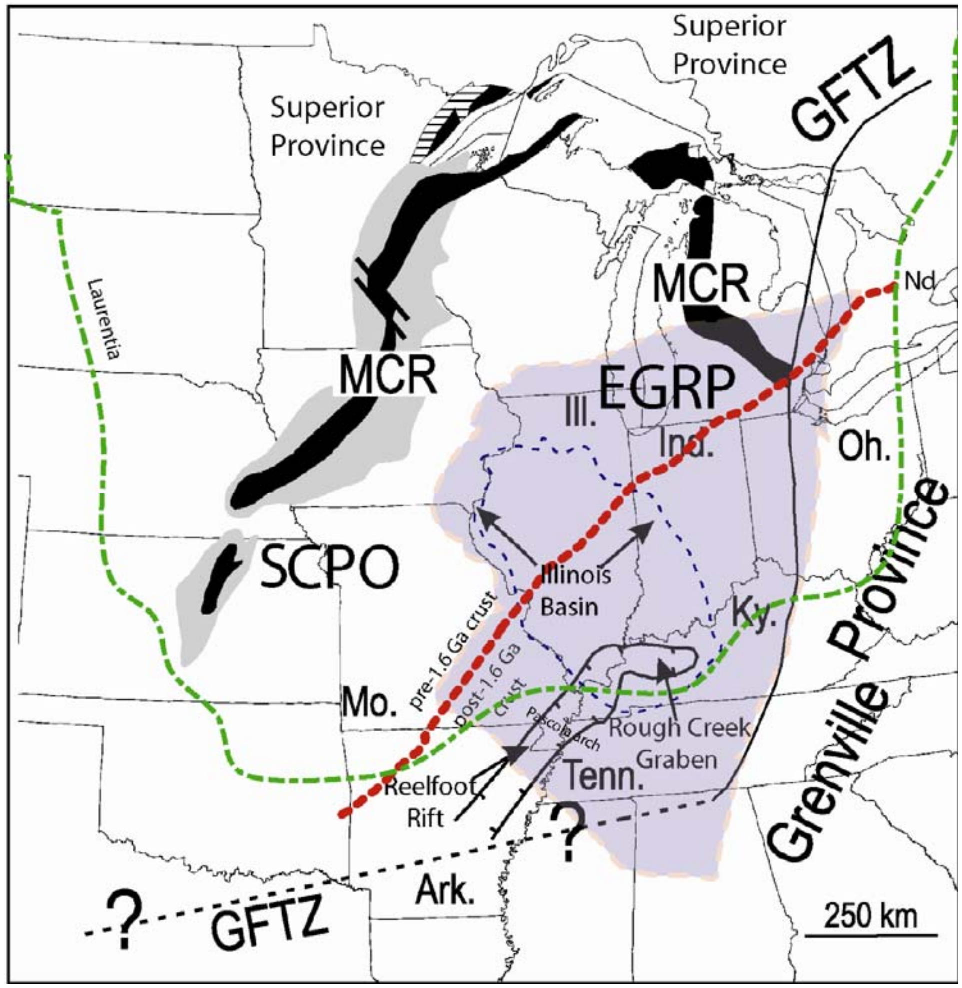
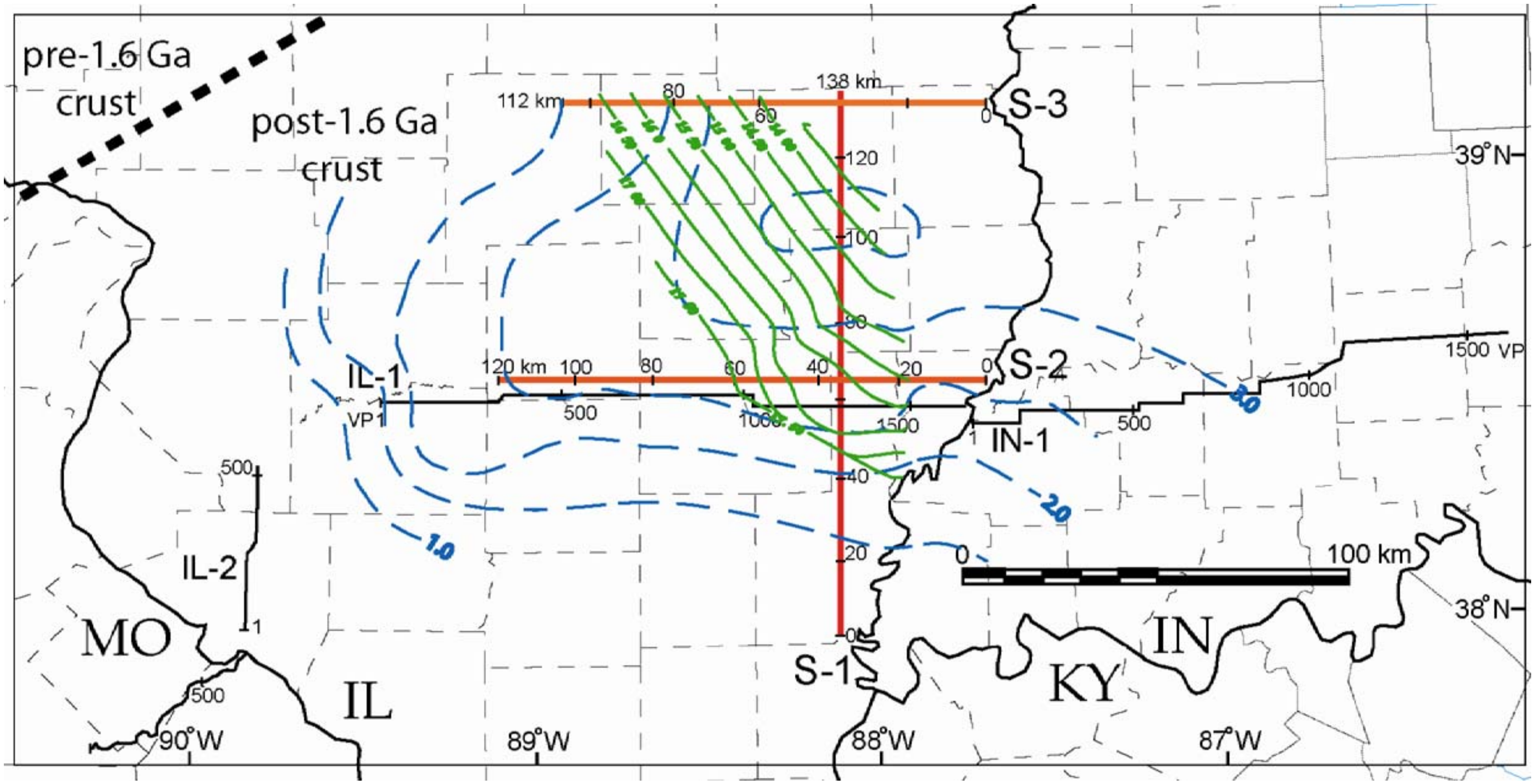

Superior Province
Superior Province
GFTZ
Laurentia
MCR
MCR
EGRP
Nd
Ill.
Ind.
Oh.
SCPO
Illinois Basin
Ky.
pre-1.6 Ga crust
post-1.6 Ga crust
Pascola Arch
Rough Creek Graben
Mo.
Reelfoot Rift
Tenn.
?
Grenville Province
Ark.
?
GFTZ
250 km

Figure 1

Figure 2.


pre-1.6 Ga crust
post-1.6 Ga crust
112 km
80
138 km
60
S-3
0
120
100
80
S-2
120 km
100
80
60
40
20
0
IL-1
VP1
500
1000
1500
IN-1
1
500
1000
1500 VP
3.0
2.0
1.0
39°N
38°N
500
IL-2
1
MO
500
IL
40
20
0
S-1
100 km
0
IN
KY
90°W
89°W
88°W
87°W

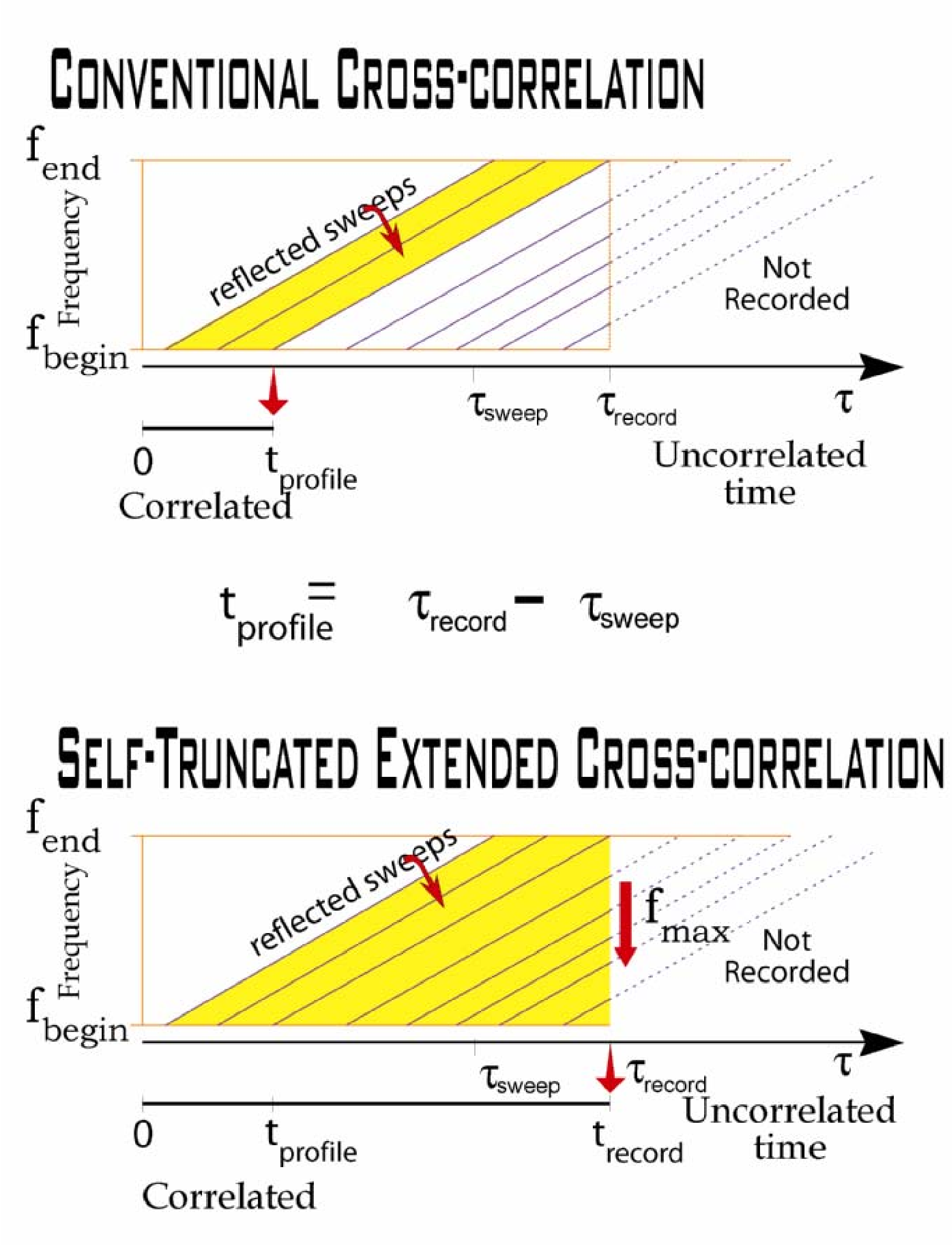

CONVENTIONAL CROSS-CORRELATION
f_{end}
Frequency
f_{begin}
reflected sweeps
Not Recorded
τ_{sweep}
τ_{record}
τ
0
$t_{profile}$
Correlated
Uncorrelated time
$t_{profile} = \tau_{record} - \tau_{sweep}$
SELF-TRUNCATED EXTENDED CROSS-CORRELATION
f_{end}
Frequency
f_{begin}
reflected sweeps
f_{max}
Not Recorded
τ_{sweep}
τ_{record}
τ
0
$t_{profile}$
t_{record}
Uncorrelated time
Correlated

Figure 3.

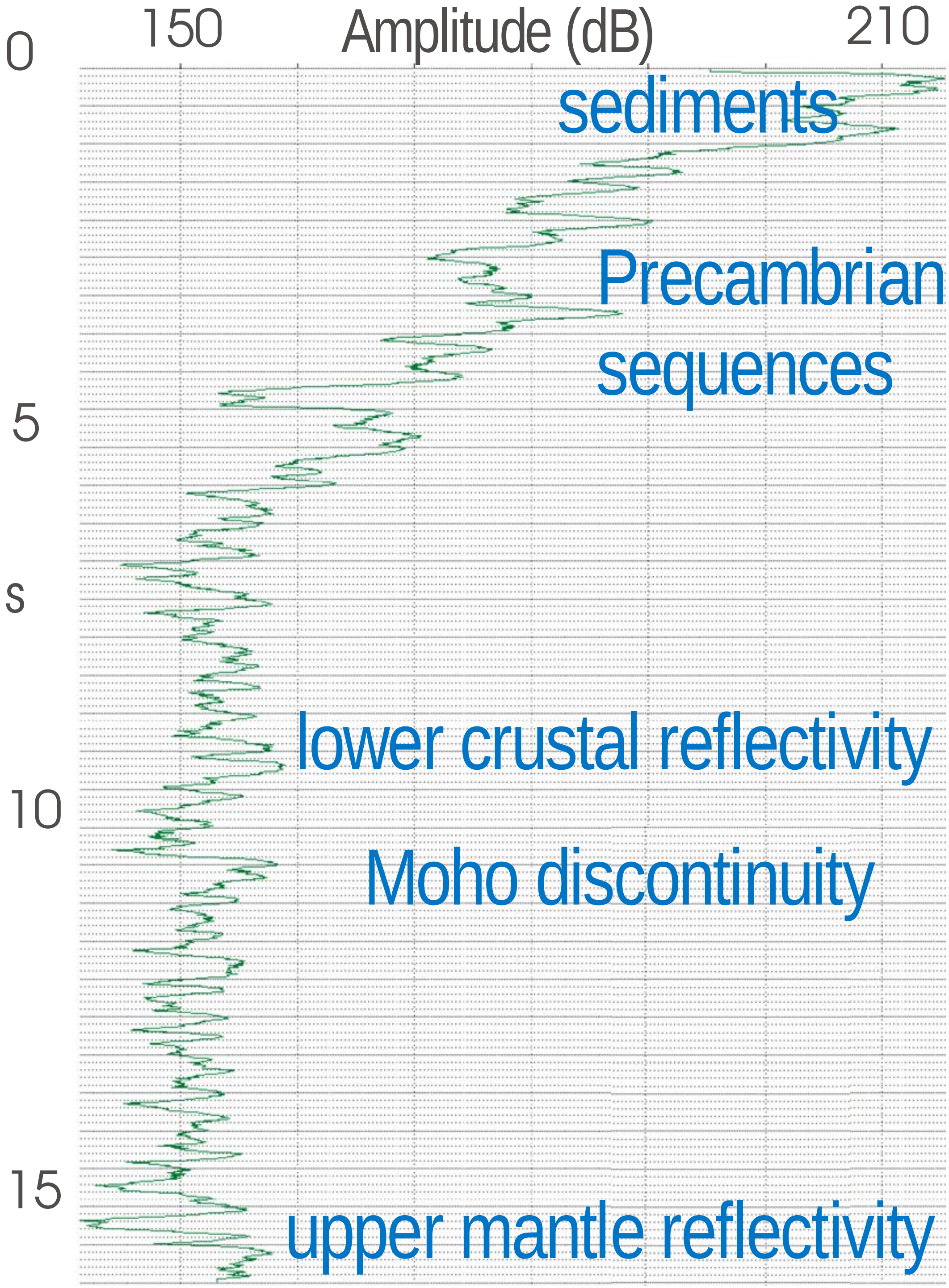

0
150
Amplitude (dB)
210
sediments
Precambrian
sequences
5
s
lower crustal reflectivity
10
Moho discontinuity
15
upper mantle reflectivity

Figure 4.

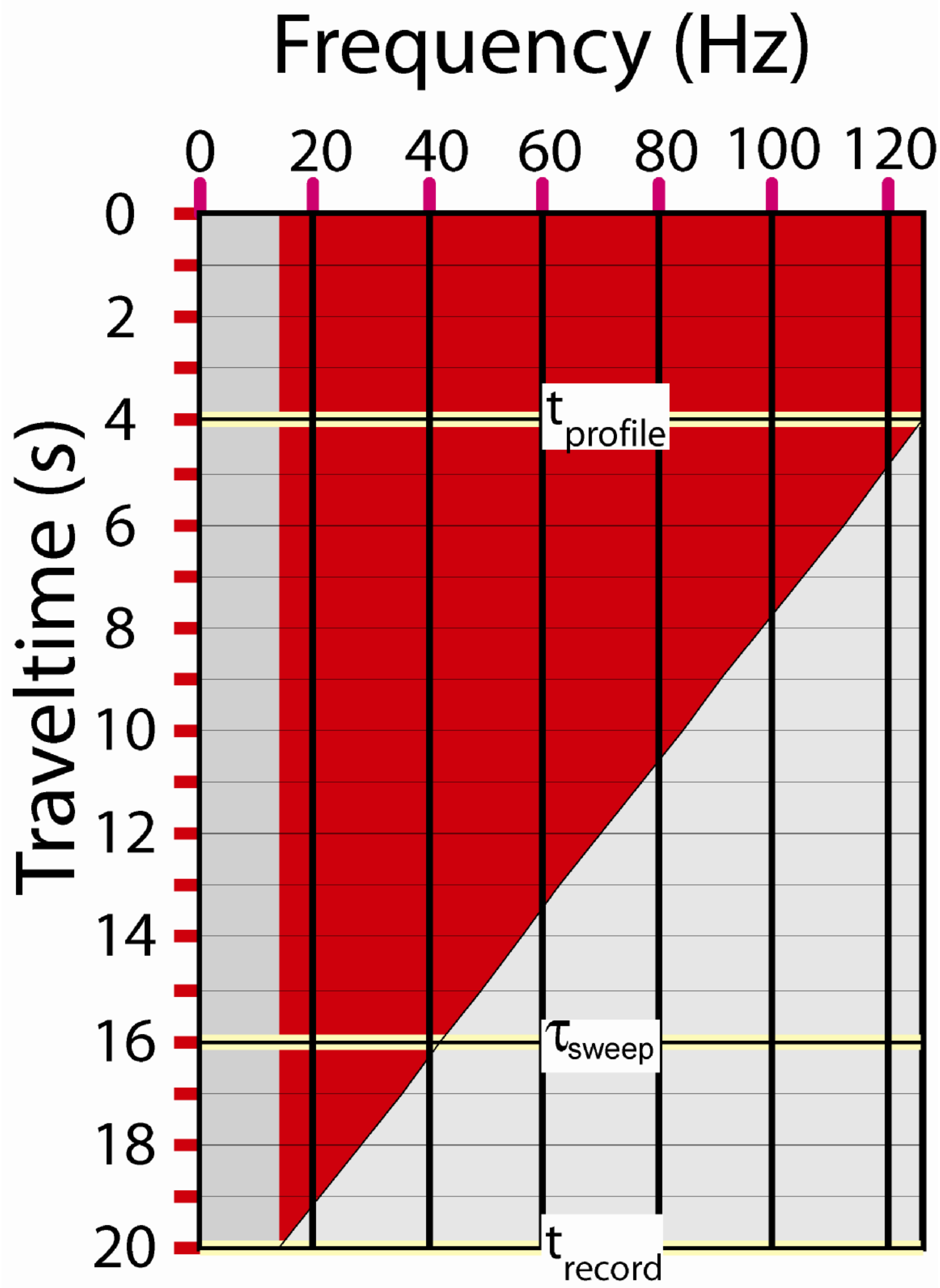

Frequency (Hz)
0
20
40
60
80
100
120
Traveltime (s)
0
2
4
6
8
10
12
14
16
18
20
$t_{profile}$
τ_{sweep}
t_{record}

Figure 5.

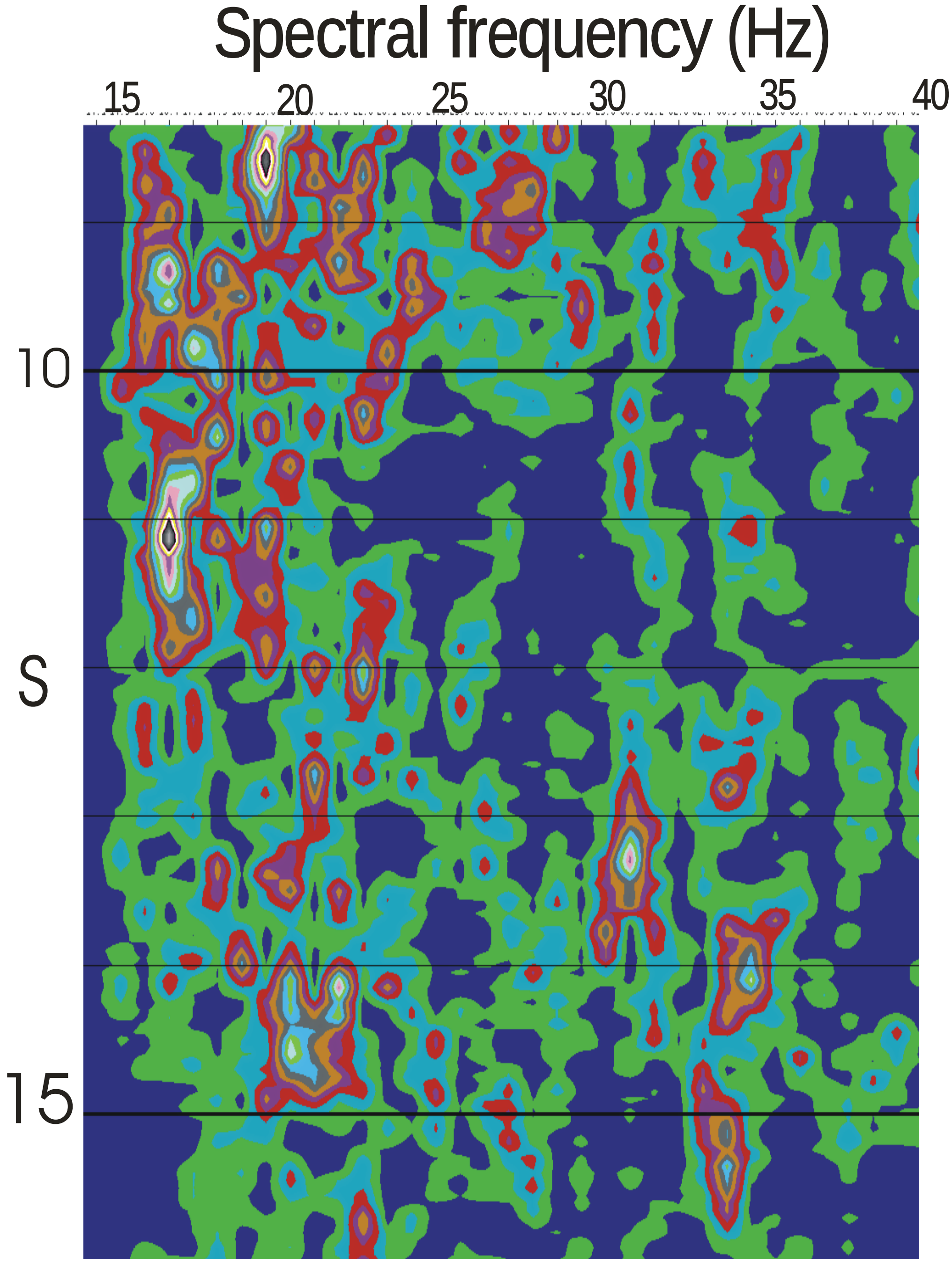
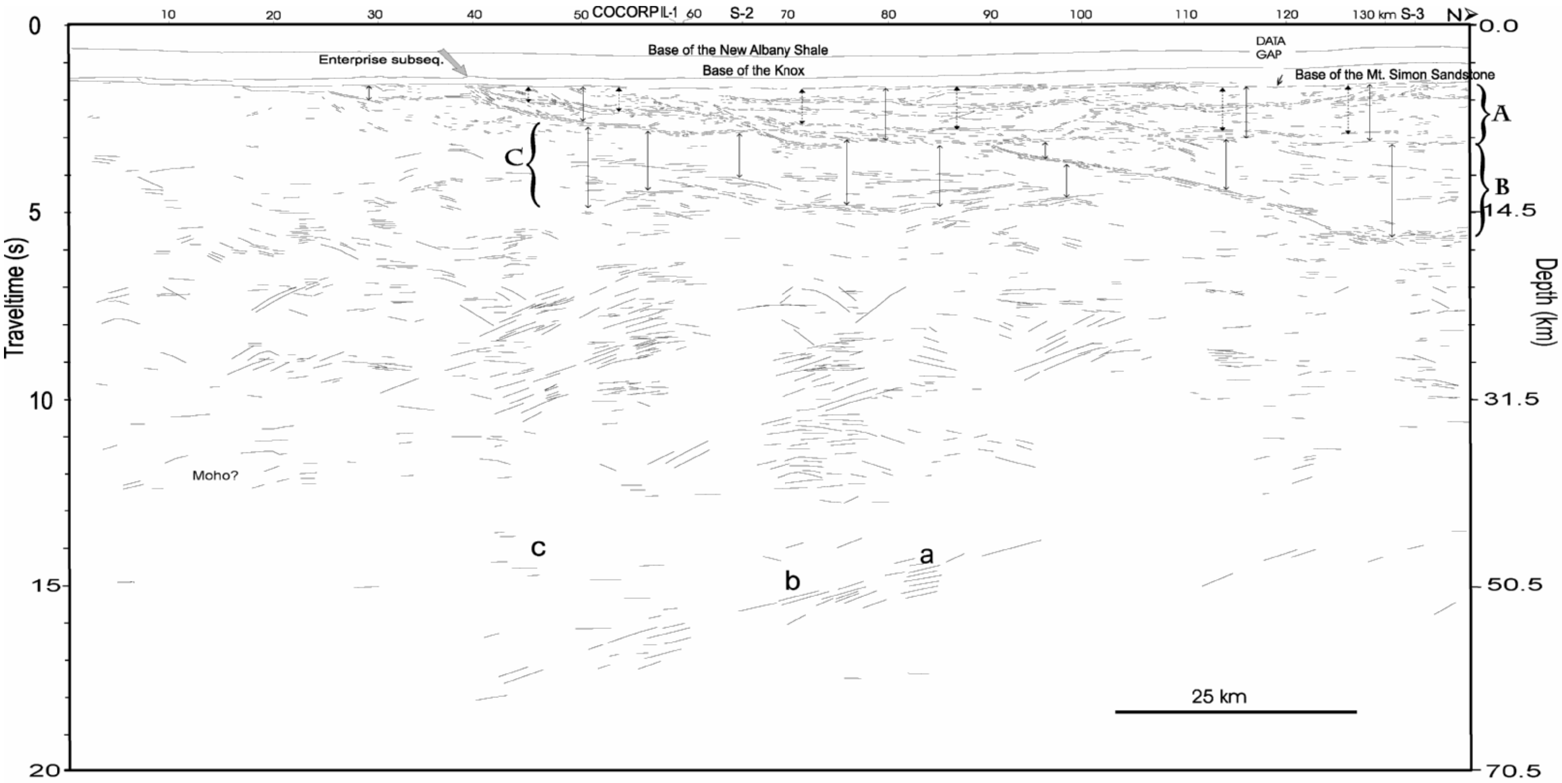


Figure 6.

Figure 7.



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

Figure 8.

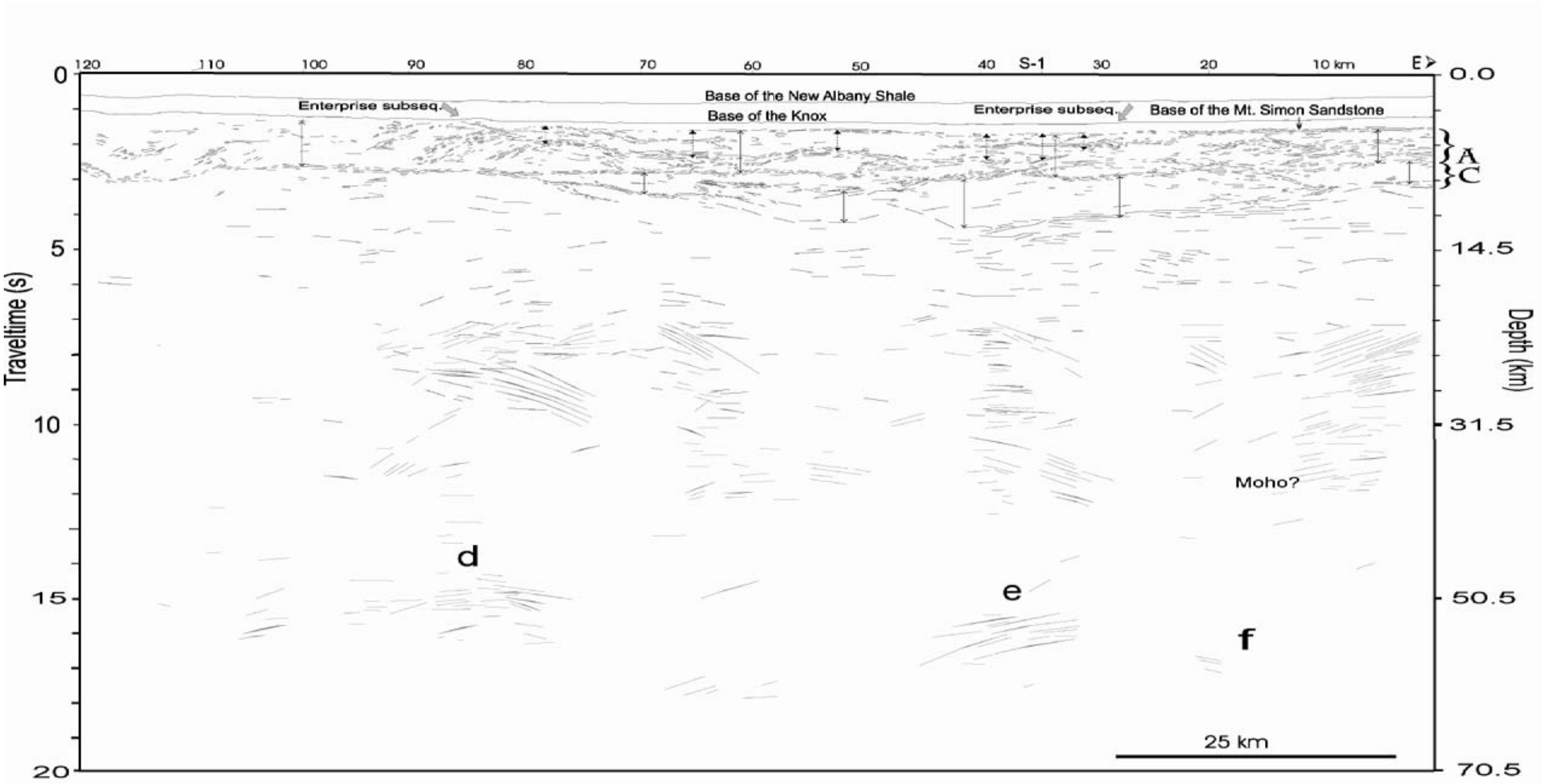
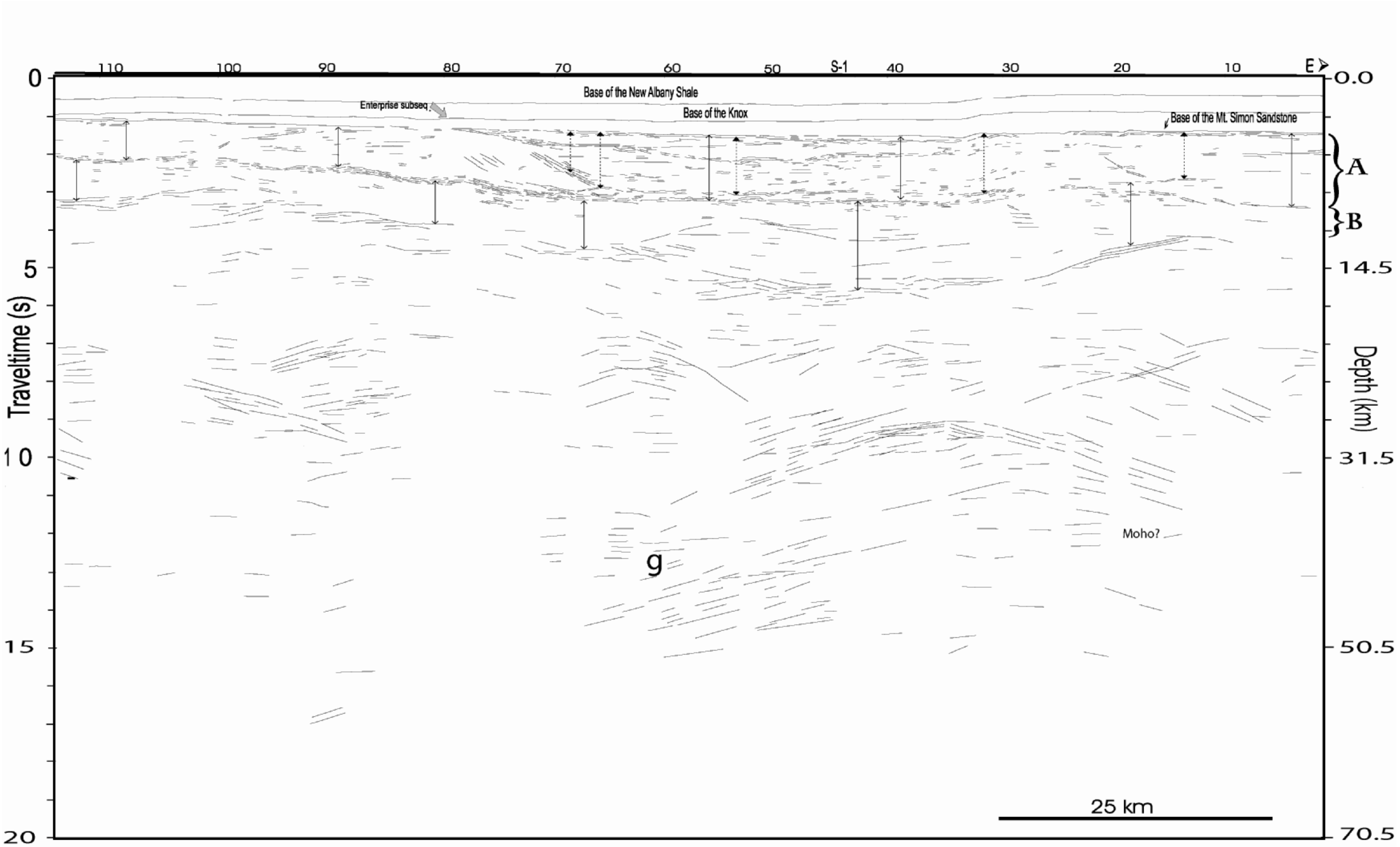

120
110
100
90
80
70
60
50
40
S-1
30
20
10 km
E
0
5
10
15
20
Traveltime (s)
0.0
14.5
31.5
50.5
70.5
Depth (km)
Base of the New Albany Shale
Base of the Knox
Enterprise subseq.
Enterprise subseq.
Base of the Mt. Simon Sandstone
A
C
Moho?
d
e
f
25 km

Figure 9.


110
100
90
80
70
60
50
S-1
40
30
20
10
E
Base of the New Albany Shale
Enterprise subseq
Base of the Knox
Base of the Mt. Simon Sandstone
A
B
g
Moho?
25 km
Traveltime (s)
0
5
10
15
20
Depth (km)
0.0
14.5
31.5
50.5
70.5

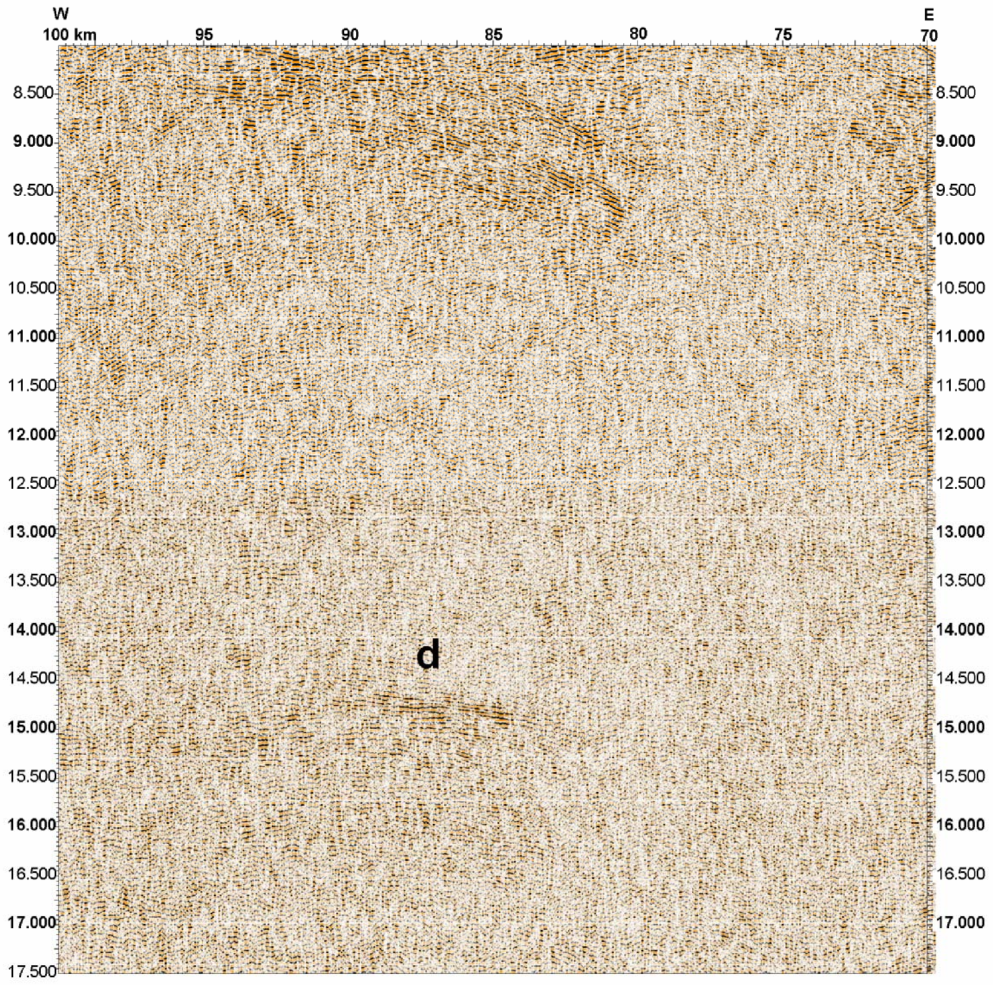
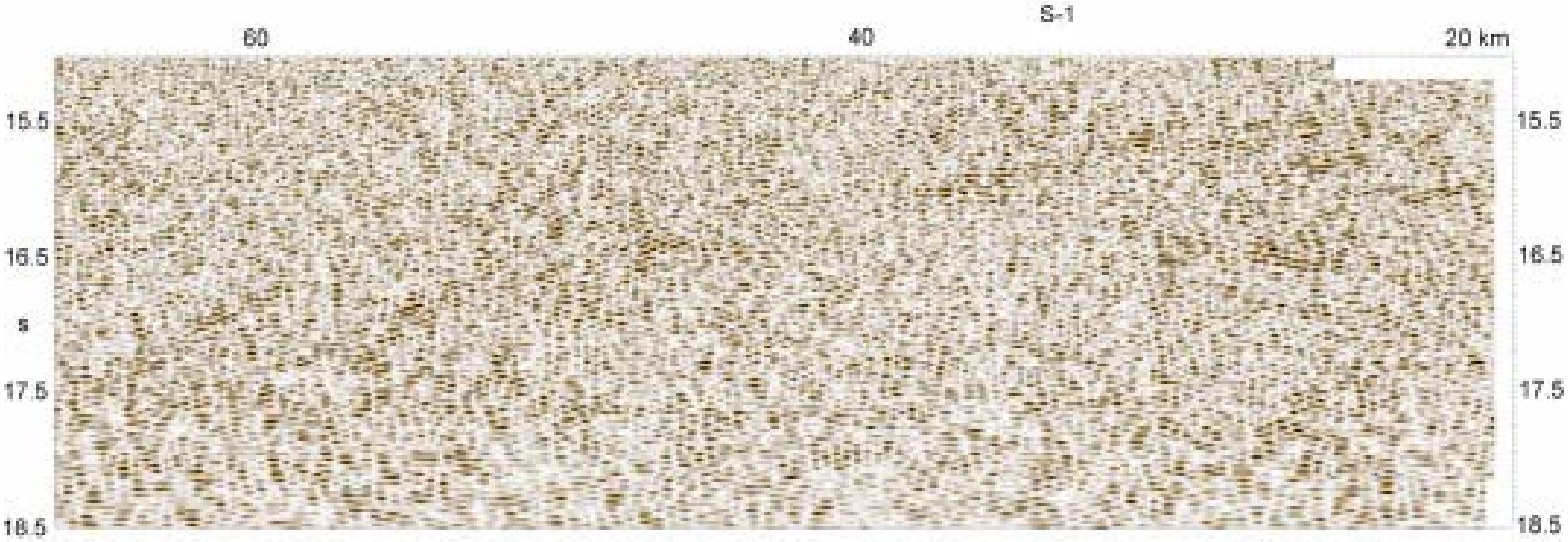

W
E
100 km
95
90
85
80
75
70
8.500
9.000
9.500
10.000
10.500
11.000
11.500
12.000
12.500
13.000
13.500
14.000
14.500
15.000
15.500
16.000
16.500
17.000
17.500
d

Figure 10.

Figure 11.



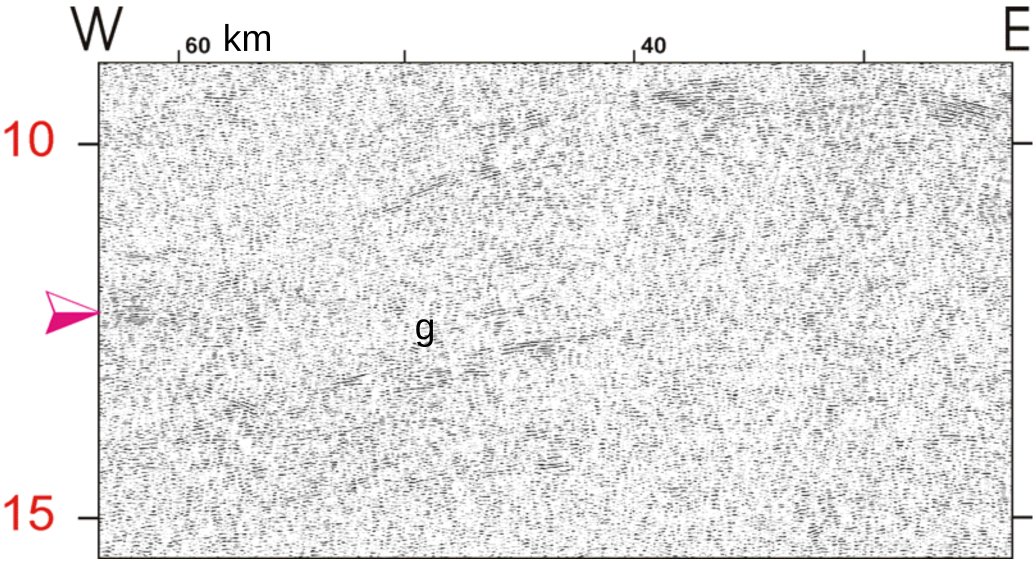


Figure 12.

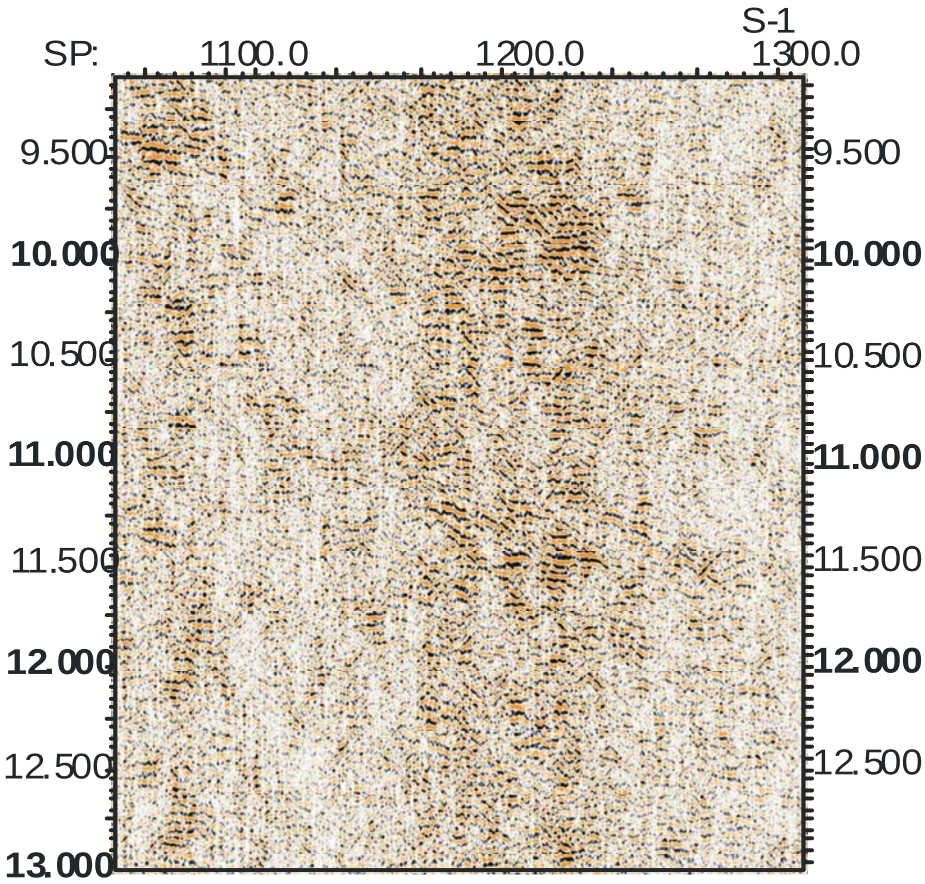


Figure 13.

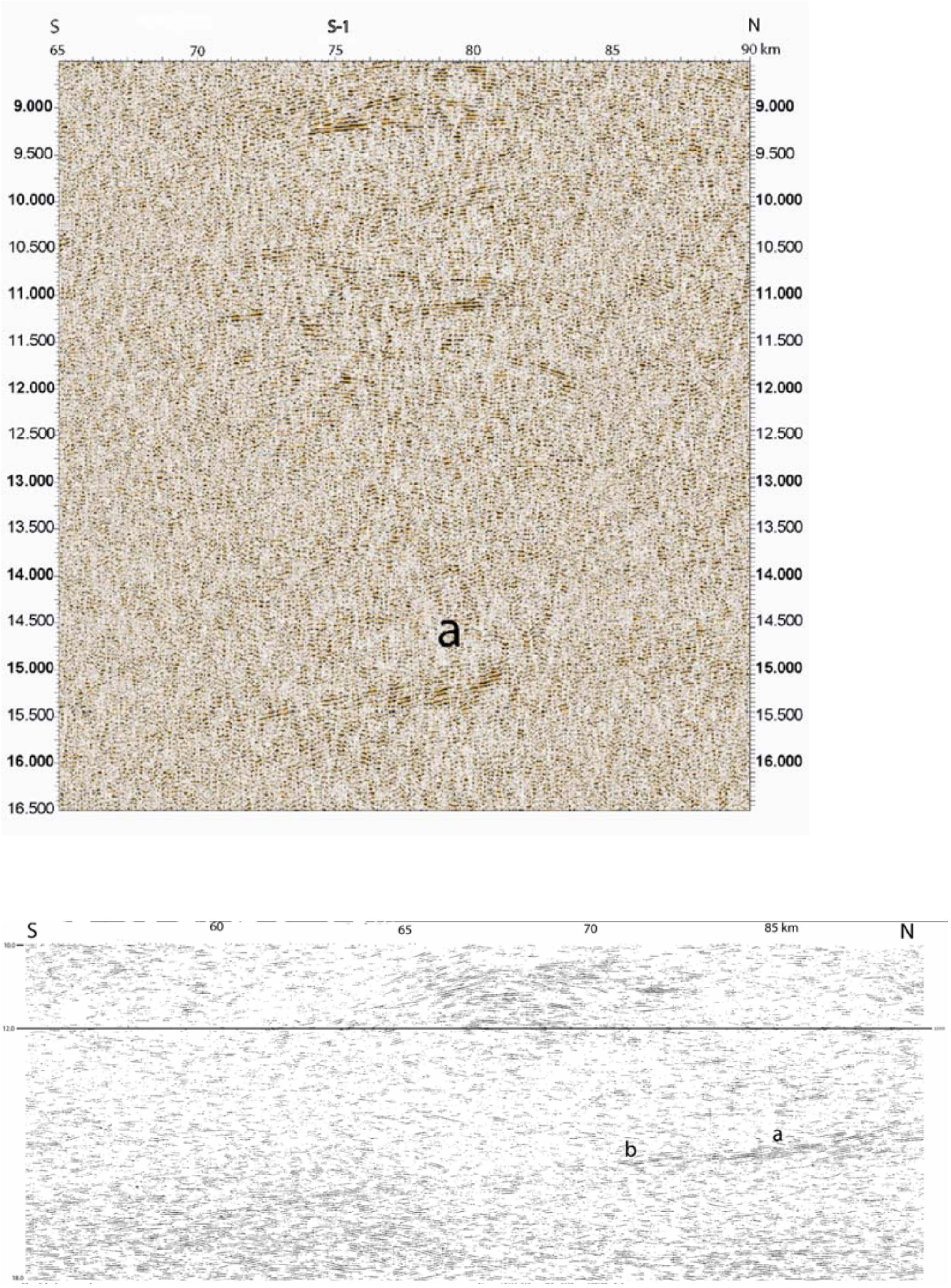

S
S-1
N
65
70
75
80
85
90 km
9.000
9.500
10.000
10.500
11.000
11.500
12.000
12.500
13.000
13.500
14.000
14.500
15.000
15.500
16.000
16.500
a
S
60
65
70
85 km
N
b
a

Figure 14.

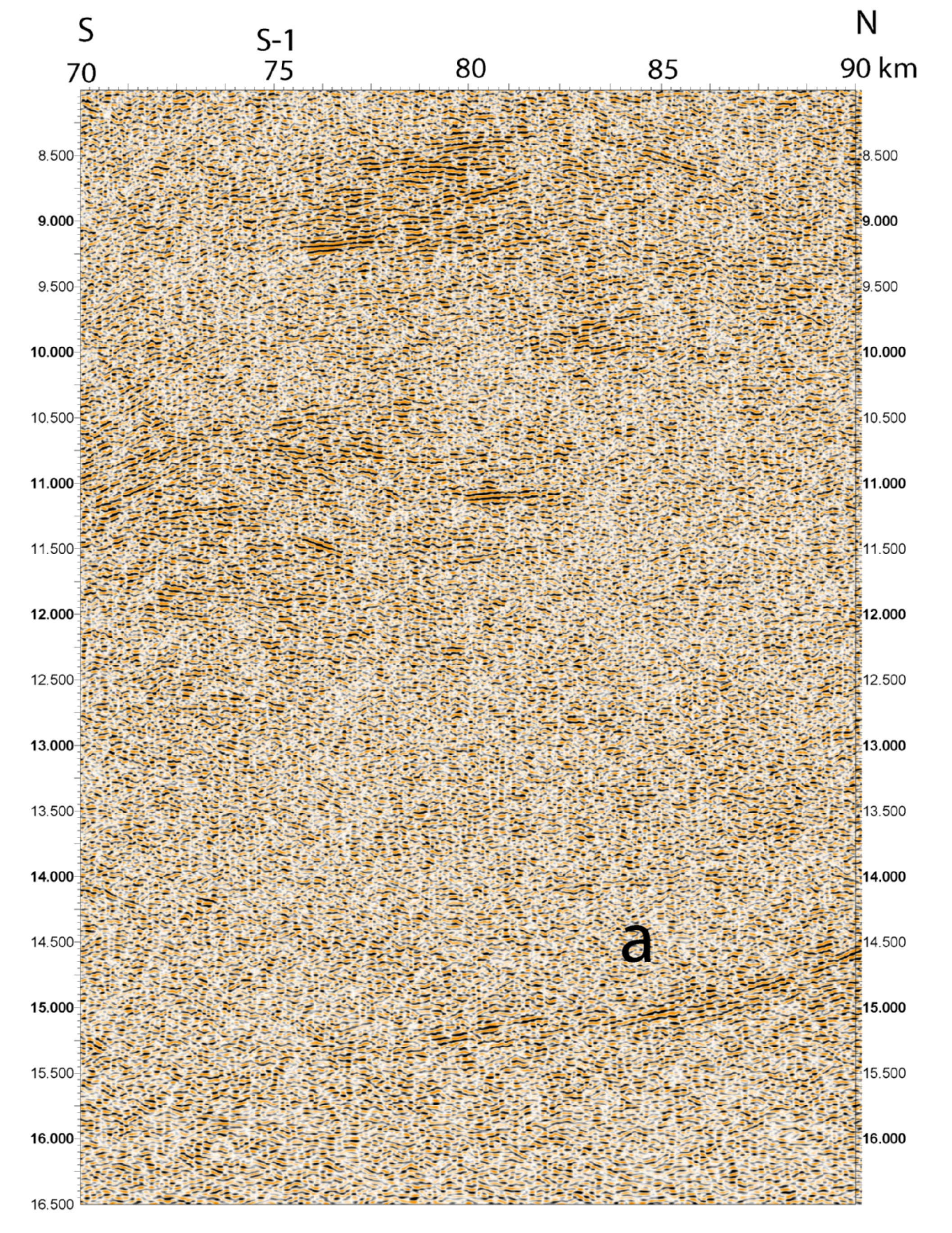
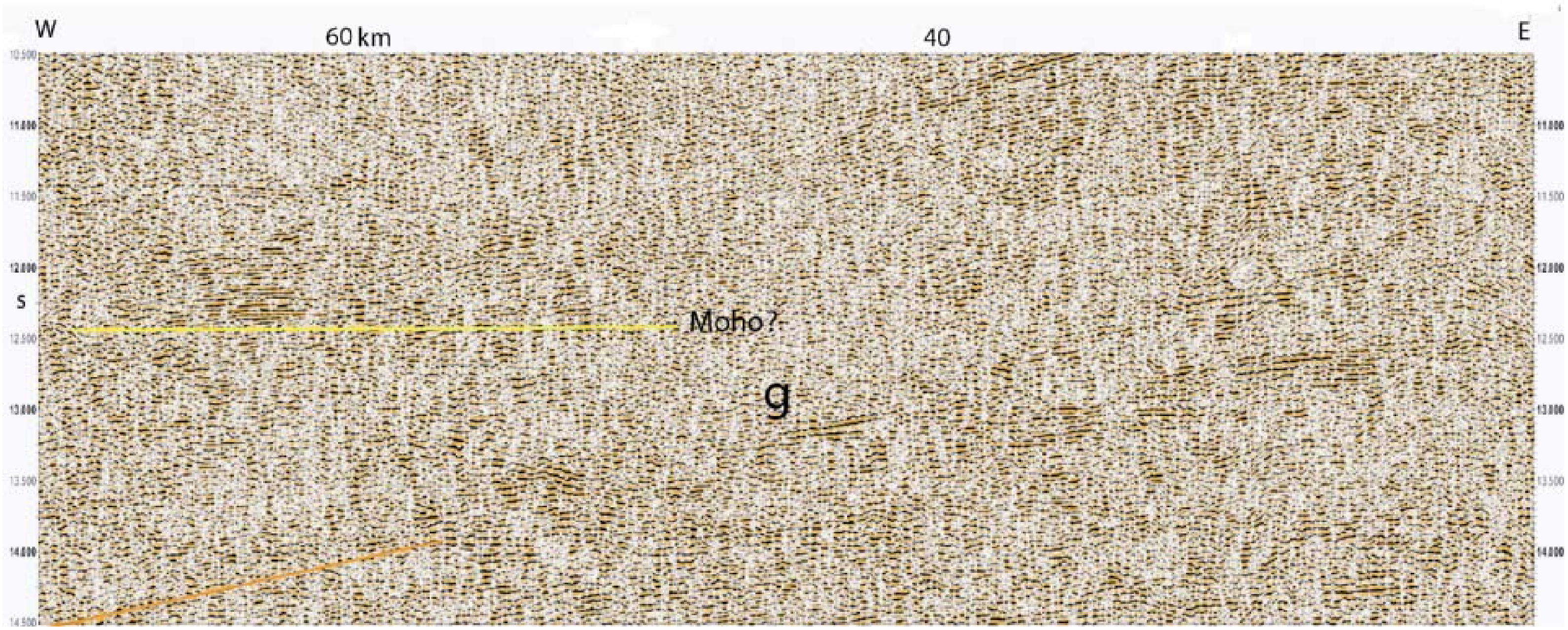
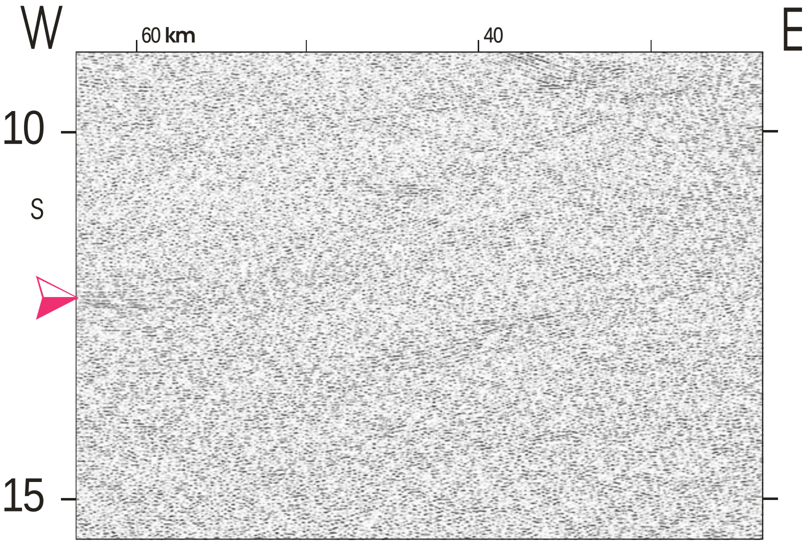

S
S-1
N
70
75
80
85
90 km
8.500
9.000
9.500
10.000
10.500
11.000
11.500
12.000
12.500
13.000
13.500
14.000
14.500
15.000
15.500
16.000
16.500
a

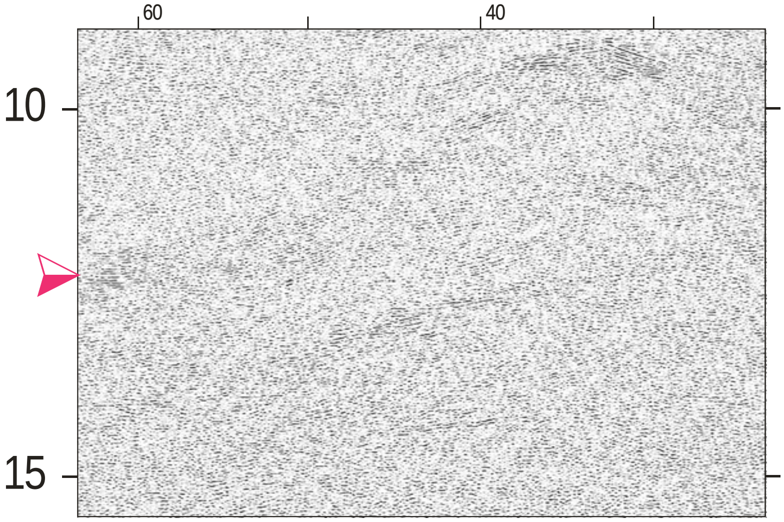
Figure 15.

Figure 16.

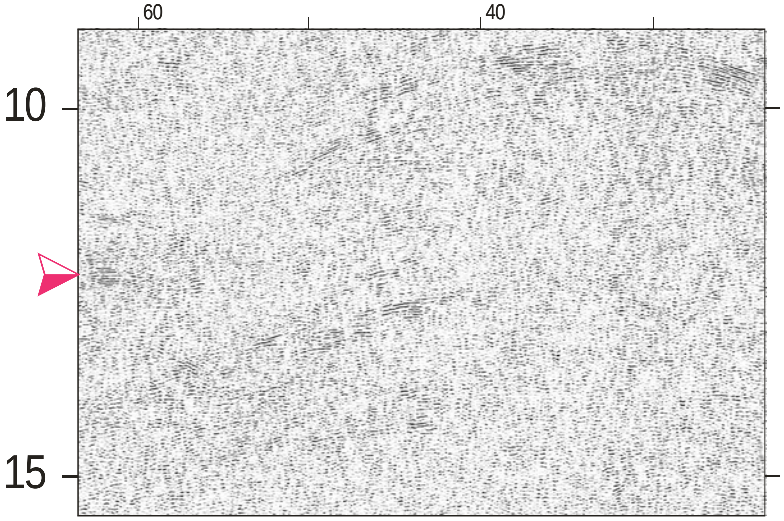

W
60 km
40
E
S
Moho?
g
10.500
11.000
11.500
12.000
12.500
13.000
13.500
14.000
14.500



8000 m/s migration constant velocity



6000 m/s migration constant velocity



Unmigrated

Figure 17.

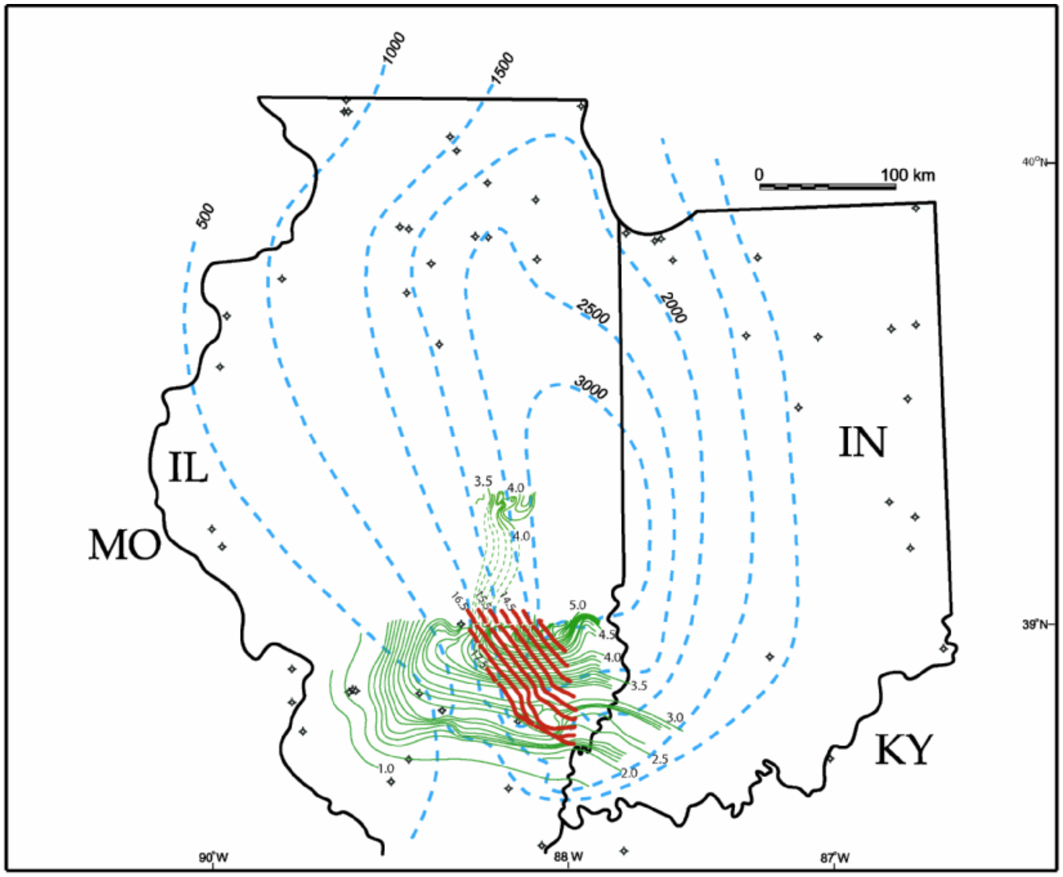

1000
1500
500
2500
2000
3000
0
100 km
40°N
39°N
IN
IL
MO
KY
3.5
4.0
4.0
16.5
15.5
14.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.0
90°W
88 W
87°W

Figure 18.

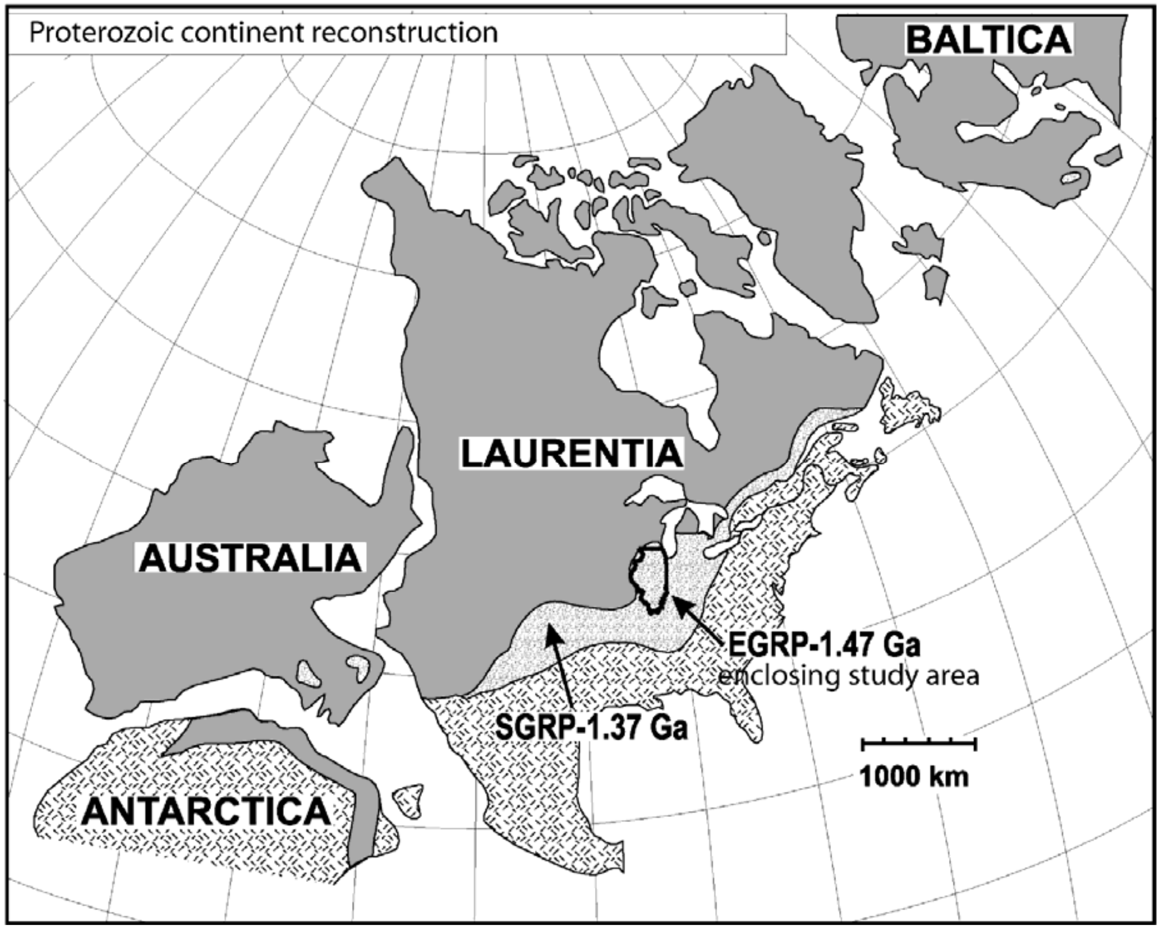


Figure 19.

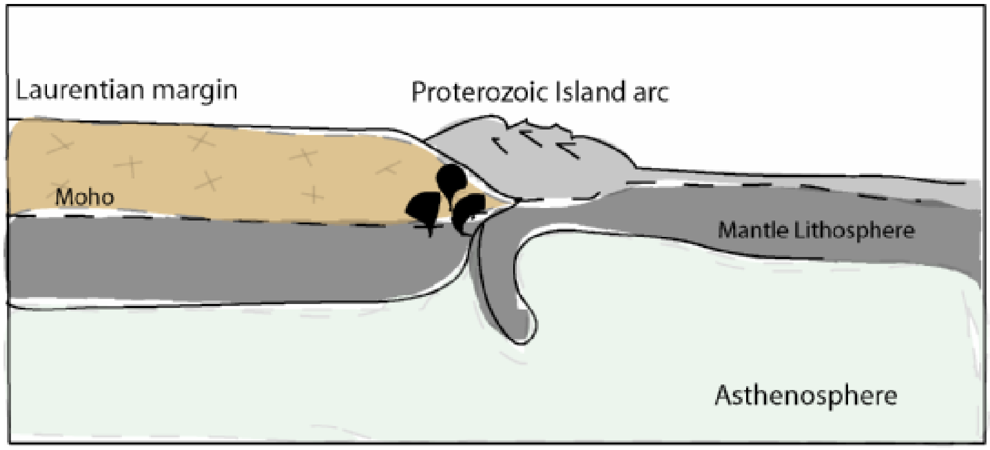


Figure 20.