From trash to treasure: Three-dimensional basement imaging with "excess" data from oil and gas explorations

Doyeon Kim and Larry D. Brown

ABSTRACT

Modern oil and gas seismic surveys commonly use areal arrays that record continuously, and thus routinely collect "excess" data that are not needed for the conventional common reflection point imaging that is the primary goal of exploration. These excess data have recently been recognized to have utility not only in resource exploration but also for addressing a diverse range of scientific issues.

Here we report processing of such discarded data from recent exploration surveys carried out in southeastern New Mexico. These have been used to produce new three-dimensional (3-D) seismic reflection imagery of a layered complex within the crystalline basement as well as elements of the underlying crust. This enigmatic basement layering is similar to that found on industry and academic seismic reflection surveys at many sites in the central United States. Correlation of these reflectors with similar features encountered by drilling in northwestern Texas suggest that they may be part of an extensive, continental-scale network of tabular mafic intrusions linked to Keweenawan rifting of the igneous eastcentral Unites States during the late Proterozoic. More importantly, this analysis clearly demonstrates that the new generation of continuously recorded 3-D exploration datasets represent a valuable source of fresh information on basement structure that should be examined rather than discarded. Such basement information is not only important to understanding crustal evolution, it is directly relevant to assessing risks associated with fossil fuel extractions, such as induced seismicity related to waste water injection.

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AUTHORS

Doyeon Kim ~ *Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, New York; dk696@cornell.edu*

Doyeon Kim is a postdoctoral fellow at the University of Maryland, College Park. Kim earned an M.S. in civil and environmental engineering from Yonsei University, Korea, and Ph.D. in geophysics from Cornell University. Kim's primary research interest is to describe and quantify both shallow and deep processes of the solid earth using seismic data and numerical models while developing new techniques for imaging structures.

Larry D. Brown ~ *Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, New York; ldb7@cornell.edu*

Larry D. Brown is the Sidney Kaufman Professor in Geophysics. Brown earned a B.S. in physics from the Georgia Institute of Technology and Ph.D. in geological sciences from Cornell. Brown's current research includes deep seismic investigations in China (especially Tibet), Mongolia, Taiwan, the Andes, and the Caribbean (Montserrat), the application of seismic interferometry to seismic body waves, imaging of crustal structure using microearthquakes, and four-dimensional seismic monitoring of deep tectonic processes.

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INTRODUCTION

Seismology has been an essential tool for probing the deep crust since Mohorovičić first provided a seismological definition of its base using refraction techniques (Mohorovičić, 1910). Beginning with the Consortium for Continental Reflection Profiling (COCORP) program in the mid-1970s (e.g., Oliver et al., 1976), systematic application of the multichannel reflection techniques developed by the oil and gas industry has led to routine reflection imaging of crustal heterogeneities around the world (e.g., Brown, 2013). Although a large fraction of the continental lithosphere has now been probed by deep reflection surveys, the vast majority of these experiments have been in the form of two-dimensional (2-D) seismic profiling. True three-dimensional (3-D) reflection surveys of the continental basement are still relatively rare. Notable examples include those associated with the Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland deep drill hole in central Germany (e.g., Stiller, 1991), a COCORP survey in southeastern Georgia (Cook et al., 1981), a LITHOPROBE survey in Alberta, Canada (e.g., Welford and Clowes, 2004), and—most relevant to this study—3-D surveys of basement layering in central Illinois (McBride et al., 2016) and Scandinavia (Hedin et al., 2016).

Recent technical advances in the oil and gas industry's capability for acquiring 3-D seismic reflection data in sedimentary basins represent a new opportunity for extracting 3-D seismic imagery of underlying basement. Prior to this time, most traditional seismic surveys were based on the "roll-along" model, in which a finite array or grid of geophones recorded a fixed time of ground vibration after a seismic source was set off (Figure 1A). Thus, the seismic recordings were tightly limited in both time and space. Today, modern nodal units are capable of recording continuously for much larger time spans (Figure 1B). Normally, only a fraction of these recordings is harvested to produce common reflection point (CRP) stacks for the intended exploration purpose (typically equivalent to a 5-s two-way traveltime or less). In fact, little of the data that lie between the recordings specifically harvested for conventional reflection imaging have been used. These "excess" data correspond to data recorded after the end of the conventional "record length" but before the beginning of the next shot. For explosive sources, this corresponds to the difference in the time between consecutive shots and the designated record length to be harvested. For vibroseis sources, this corresponds to the difference between initiation of the sweeps that constitute a specific shotpoint and the total record length (sweep length plus additional record length). Of course, efficient survey operations try to minimize such

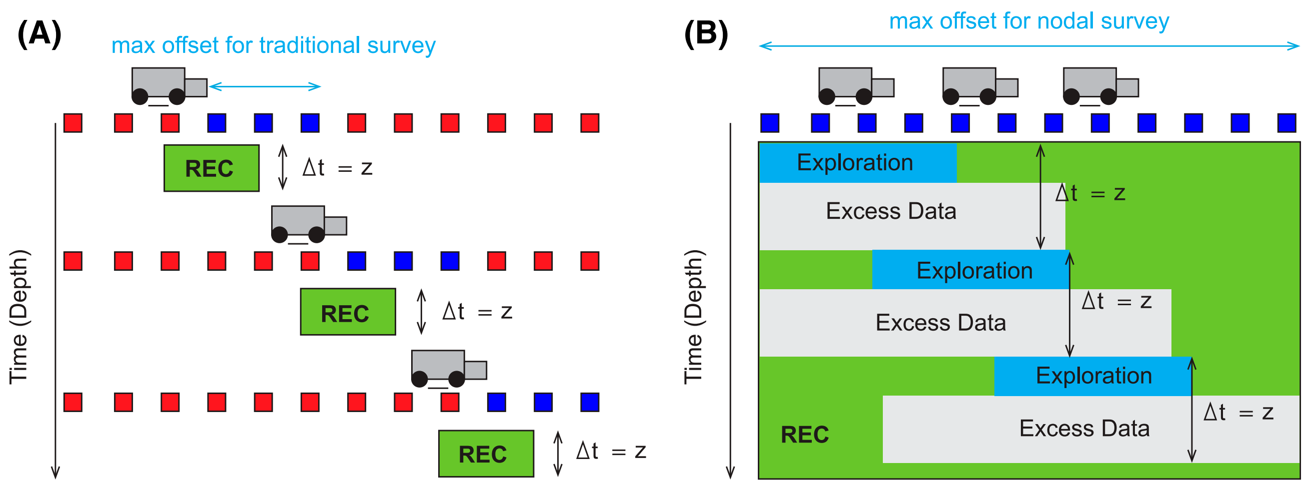

Figure 1. A comparison of (A) traditional roll-along multichannel reflection profiling with (B) modern nodal recordings. Blue and red squares are active and inactive channels, respectively. The green box labeled as "REC" represents recording in time and space. Light blue arrows show maximum source-receiver offset. Note that all channels record for the full duration of the nodal survey. The blue boxes represent the subset of the recordings that is typically harvested for exploration purposes. The green and gray boxes represent surplus recordings that contain nominally untapped information. The gray boxes correspond specifically to recording of deep reflections beneath the zone of direct exploration interest. Δt = recording time; z = imaging depth.

excess recordings. Even if there is no excess recording, the lack of correlation in the field leaves open the possibility of recovering deep reflections by the extended correlation technique, as used in this study. However, these "interstitial" or excess data contain a wide variety of information that can be used for diverse studies, including (1) ground motion caused by natural ambient noise that can be used to map subsurface velocity variations using seismic interferometry (e.g., Lin et al., 2013); (2) vibrations caused by cultural noise (e.g., Nakata et al., 2011; Quiros et al., 2016); (3) seismic arrivals from local earthquakes (e.g., Inbal et al., 2015); and (4) teleseismic arrivals (e.g., Schmandt and Clayton, 2013). Within the exploration context, there is growing recognition that the ambient noise component can also provide low-frequency information that can enhance conventional reflection imagery and subsequent velocity inversion (e.g., Bussat and Kugler, 2011).

Of primary interest here is that such surveys will likely contain reflection energy that has probed the crystalline basement, arriving back to the array at traveltimes that exceed that harvested for resource exploration purposes. In short, this new generation of industry surveys constitutes a systematic exploration of the continental basement using high-resolution 3-D seismic reflection techniques as a no-cost (at least in terms of field acquisition) byproduct. This demonstration analysis uses a small subset of a recent 3-D seismic survey in the Permian Delaware Basin of southeastern New Mexico (Figure 2B) that was conducted by Fairfield Nodal and provided to Cornell University for the purpose of this study. The 3-D basement imagery produced from this data set reveals details of Precambrian basement layering that we interpret to be correlative with upper crustal layering first reported in the late 1970s from COCORP crustal reflection surveys in northcentral Texas and southern Oklahoma (Brewer et al., 1981) and subsequently recognized on academic and reprocessed industry data over a large portion of the central United States (Pratt et al., 1989; McBride and Kolata, 1999; McBride et al., 2003).

DATA PROCESSING AND METHODOLOGY

The Permian Basin of western Texas and southeastern New Mexico (Figure 2B) was formed during the late Proterozoic and was subdivided into smaller basins because of subsequent tectonism in the Paleozoic (Keller et al., 1980). The geologic province extends from the Diablo platform in the west to the Midland Basin to the east (Ward et al., 1986). The central part of the basin is dominated by a major north-south–trending fault zone associated with the uplift of the Central Basin platform (Hills, 1984). Since 1921, when oil was first discovered in Mitchell County, Texas, hydrocarbon exploration in the basin has been intensive (Montgomery et al., 1999). The Permian Basin is currently the largest oil and gas deposit actively being explored in the United States (Gaswirth and Marra, 2015).

The sample of seismic data examined here was collected using 16-s-duration vibroseis signals and harvested as 21-s uncorrelated shot gathers. In this data set, 2562 shots were recorded by the same number of geophones. Receiver spacing was 50 m (164 ft) along inlines, which are spaced 250 m (820 ft) apart. Source spacing was 50 m (164 ft) but along crosslines, spacing was also 250 m (820 ft) apart. Ideally, for deeper imaging, one would want to reharvest the original field recordings for longer data windows. In our case, the conventionally harvested data were more immediately available. However, because these data were provided in uncorrelated form, the depth of potential reflection recovery could be increased by the well-known technique of extended correlation (e.g., Okaya and Jarchow, 1989). As can be seen from Figure 3B, significant energy was retained in the range of 10–20 Hz at basement traveltimes.

Extended correlation essentially trades bandwidth for additional traveltime. Because an upsweep was used in the survey, the bandwidth loss will occur at the higher frequencies (e.g., Figure 3B), which are less effective for deeper penetration because of attenuation. Figure 3D illustrates extended correlation as applied to a sample shot gather down to 15 s. After extended correlation, 2-D profiles and a 3-D reflection volume were produced with relatively conventional CRP processing routines (e.g., Yilmaz, 2001). The key components of this processing were as follows: (1) trace editing to eliminate noisy traces, (2) bandpass (10–20 Hz) filtering to emphasize deeper reflection signals, (3) CRP velocity analysis (e.g., Figure 3E), (4) normal moveout correction, and (5) CRP stack (25×25 m [82×82 ft] binning).

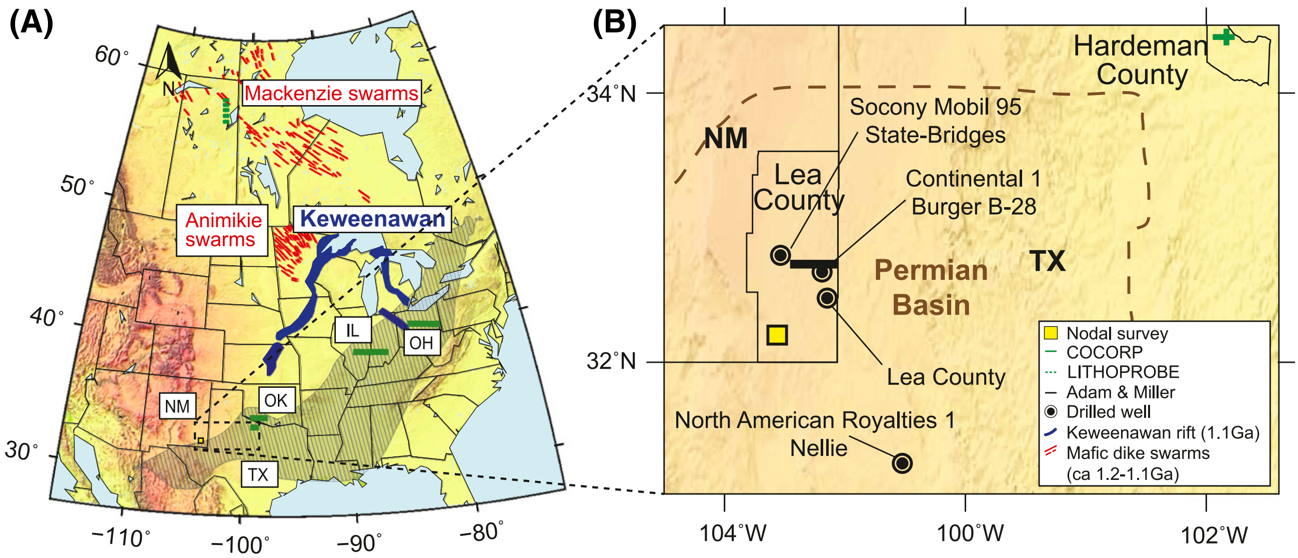

Figure 2. (A) Location of the study area (dotted box) relative to key terranes of the Precambrian basement of the central United States. Major elements of Keweenawan rifting are shown in dark blue. The earlier Mackenzie and Animikie dike swarms are depicted in red. The gray-shaded region in the midcontinent United States represents the granite-rhyolite terrain (Whitmeyer and Karlstrom, 2007). Green solid and dotted lines correspond to continental reflection surveys by the Consortium for Continental Reflection Profiling (COCORP) and LITHOPROBE, respectively. (B) Portion of a three-dimensional exploration survey conducted by Fairfield Nodal (yellow square) in the Permian Delaware Basin (brown dashed line) of southeastern New Mexico, from which the data used in this study were obtained. Thick green and black lines correspond to reflection surveys by COCORP (Brewer et al., 1981) and Adams and Miller (1995), respectively. Black dots indicate the location of relevant nearby wells (Muehlberger et al., 1966). IL = Illinois; OH = Ohio; OK = Oklahoma; NM = New Mexico; TX = Texas.

Poststack 3-D frequency–wavenumber migration was applied to the final CRP stacked volume.

RESULT AND INTERPRETATION

Crustal versus Nodal Survey

Comparison (Figure 4) of the 2-D sections reprocessed from nodal data with a previous reported COCORP crustal profile in the same basement terrane (Oliver et al., 1976) illustrates both the limitation and advantages of the new imagery. Although many similarities are found in both survey results, especially in the upper 5 s, the amplitude and continuity of deeper events are more prominent for the COCORP image. This is expected because the acquisition parameters for the crustal survey were chosen specifically for deep imaging, whereas those for the nodal survey were keyed to their much shallower sedimentary targets.

For example, the source effort for the COCORP survey was much greater than that for the nodal survey. To be specific, the COCORP data shown in Figure 3 used a 10-to-32-Hz vibroseis sweep generated from 5 vibrators with 16 sweeps vertically stacked per record. Each of these records was collected using a 15-s sweep and harvested as 30-s raw data. In contrast, the source effort used for the nodal data consists of three vibrators using a total of three sweeps summed per record. Neglecting any differences in the size of the vibrators used, this corresponds to a source effort that was less than 20% of that of the COCORP survey. In addition, the total length of data harvested in the nodal survey (i.e., 21-s raw data with 16-s-duration vibroseis sweep) is only 70% of that of the COCORP data. Of course, a longer record length could be harvested from the original nodal data if it were available.

The gradual decay of the source-generated energy observed from the COCORP profile contrasts with the rapid decay with traveltime for the nodal survey (Figure 3A). Note that amplitude decay after 5-s traveltimes for the nodal surveys includes the energy-truncating effect of extended correlation. However, this does not imply the total absence of reflection energy at those times (Mayer and Brown, 1986). The smaller source effort used in the nodal survey is

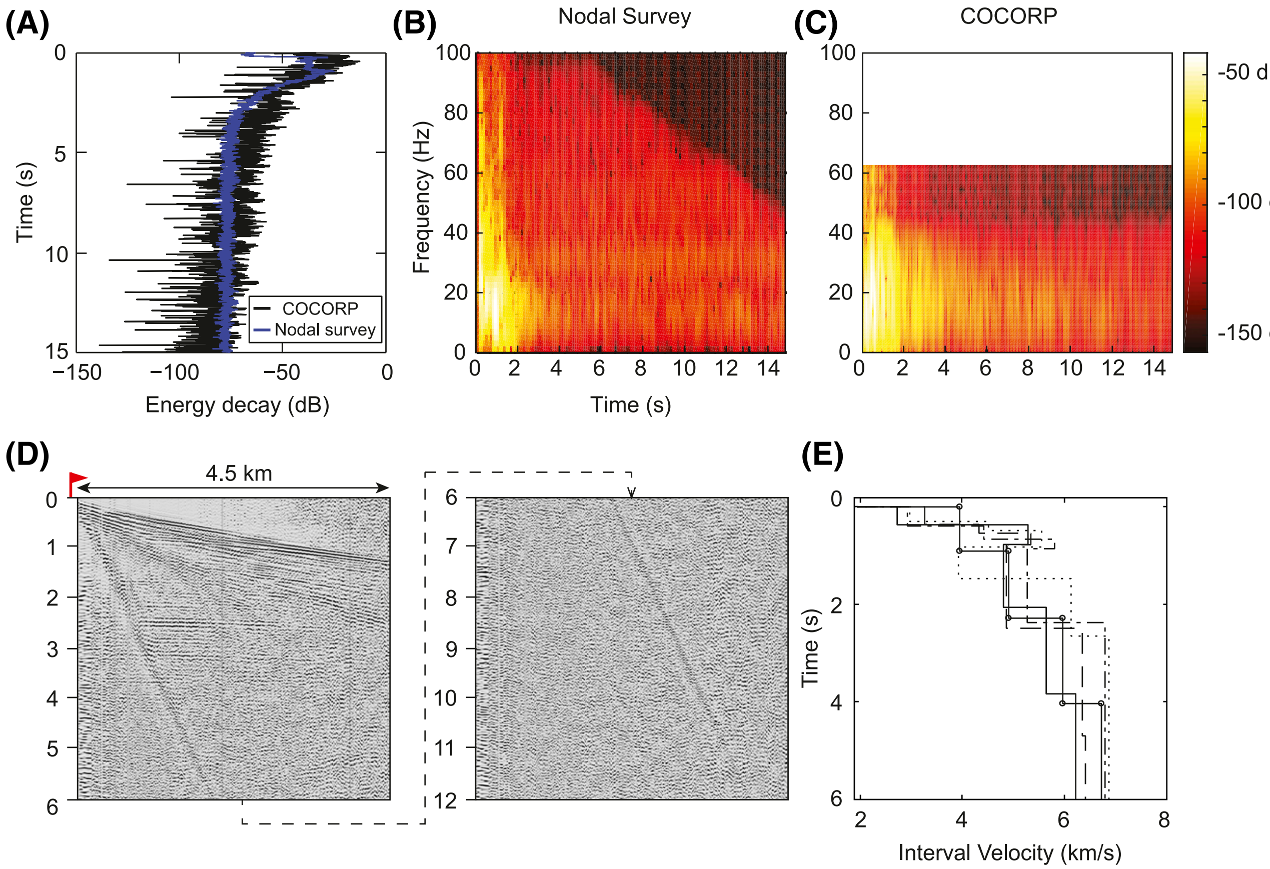

Figure 3. (A) Average energy ($10\log_{10}$ amplitude^2) of 19 correlated traces corresponding to source-receiver offsets of 400 m (1300 ft) for the nodal data (blue line) compared with a Consortium for Continental Reflection Profiling (COCORP) deep reflection survey collected in 1976 (black line). Traces are normalized relative to the amplitudes at 15 s in each case. Spectrogram for nodal traces (B) compared with COCORP traces (C). Because of the lower sampling rate of the COCORP survey, no information was recorded above 62.5 Hz. Note that the nodal result retains the same bandwidth as the COCORP data down to 15 s. (D) A typical shot gather (wrapped around at 6 s) produced by extended correlation of nodal data. Red flag represents the location of vibroseis source. Prominent reflection energy is visible to traveltimes of at least 4 s, with weaker coherency recognizable even at later traveltimes. (E) Interval velocities computed from common reflection point analysis of the nodal data.

compensated in part by the greater stacking fold for the 3-D geometry, nominally 53 versus 12 for the COCORP profile. Even so, there is certainly a notable difference in quality of the two data sets at larger traveltimes, with the COCORP section exhibiting stronger, albeit discontinuous, reflections in the deep crust (Figure 4). However, the key point is that the penetration of the nodal survey is more than sufficient to provide useful information at basement depths; despite differences in quality, both sections are characterized by a sequence of strong layered reflections down to two-way traveltimes of at least 4 s, with intermittent reflections at greater times (Figure 4). Furthermore, the nodal data set is 3-D versus 2-D for the COCORP data and is essentially a "free" byproduct of a survey carried out for purely exploration purposes.

Interpretation

Figure 5 shows the upper crustal part of a 2-D seismic section reprocessed from the nodal exploration survey in New Mexico, along with a previously reported industry seismic reflection section from nearby west Texas (Figure 2B), which also shows a layered upper basement. Although this layered character would suggest sedimentary rocks, wells in the vicinity (Figure 2B) suggest otherwise. For example, the Socony Mobil 95 State-Bridges in Lea County (Figure 2B) encountered 0.6 m (2 ft) of medium-grained micrographic granite porphyry at a depth of 4.2 km (13,779.5 ft) under the Phanerozoic strata of the Delaware Basin (Muehlberger et al., 1966). The stacking velocity of 4.4 km/s

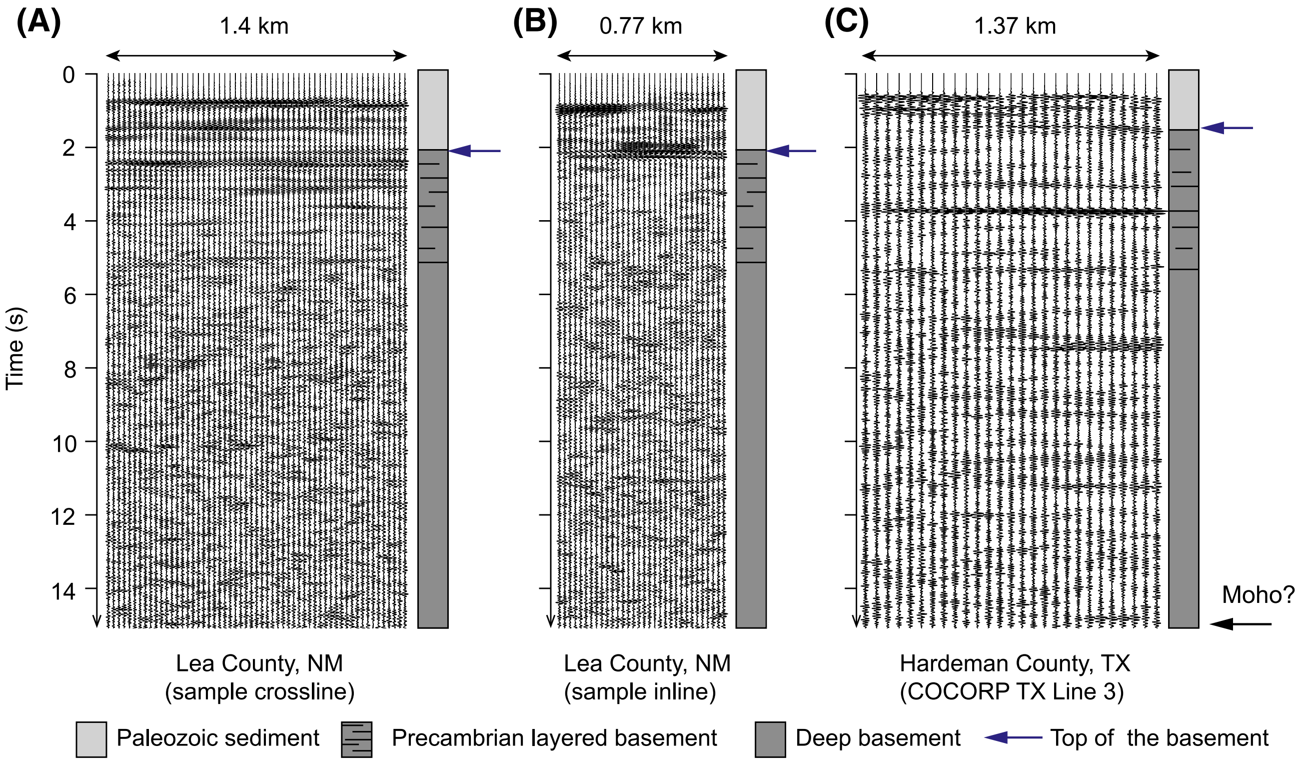

Figure 4. (A, B) Two-dimensional (2-D) common reflection point (CRP) stacked sections extracted from the three-dimensional data volume produced in this study (southeast New Mexico [NM]) and (C) stacked sections from a 2-D Consortium for Continental Reflection Profiling (COCORP) profile in Hardeman County. The blue arrows indicate the top of Precambrian basement as reported from drill holes near each survey, respectively. Mohorovičić discontinuity (Moho?) is expected at times greater than 14 s in this area (Oliver et al., 1976). Note that the CRP spacing for the nodal profile is 25 m, in contrast with that for the COCORP survey (100 m [330 ft]). TX = Texas.

(14,436 ft/s) (obtained from CRP analysis of the nodal data; Figure 3E) suggests that a depth of 4.2 km (13,779.5 ft) should correspond to 1.9 s. Thus, any primary reflections from later than this time must lie within the Precambrian basement. All of the samples collected from drill wells in Lea County, New Mexico, as documented from Bickford et al. (2015), indicate the existence of basement rocks, commonly granitic in composition.

On the basis of the layered reflection character and its location beneath the granite-rhyolite province (GRP; Figure 2A), we interpret this layered basement sequence to be correlative with the basement reflections first reported from COCORP surveys (e.g., Figure 4C) in 1975–1981 in northern Texas and southern Oklahoma (Oliver et al., 1976; Brewer et al., 1981). This layered sequence was originally interpreted as Proterozoic sedimentary rock or metasedimentary rock (Brewer et al., 1981). Comparable reflections were later observed on COCORP seismic profiles in Illinois, Indiana, and Ohio. These reflections were argued to be an accumulation of rhyolitic flows, perhaps with the occasional granite intrusion, based on the spatial correlation with the GRP (Pratt et al., 1989). However, the thickness of the layered sequence (~5 km [~16,404 ft] or more) seems extreme in comparison with the observed thickness of mapped silicic volcanic deposits (Bonnichsen and Kauffman, 1987; Henry et al., 1988; Green and Fitz, 1993). McBride and Kolata (1999) suggested that similar reflections identified on reprocessed industry profiles in central Illinois may correspond to a volcanic-sedimentary assemblage related to Keweenawan rifting, though they also point out the striking similarity of these reflections to those seen on seismic profiles from Fennoscandia that have been confirmed by drilling to be mafic sills (e.g., Juhlin, 1990). McBride et al. (2003) further argued that the Illinois Basin basement reflectivity was perhaps analogous to mafic igneous rocks associated with GRP basement exposed in the St. Francois Mountains. McBride et al. (2016) used 2-D and 3-D seismic lines collected as part of a US Department of Energy–sponsored carbon sequestration study in

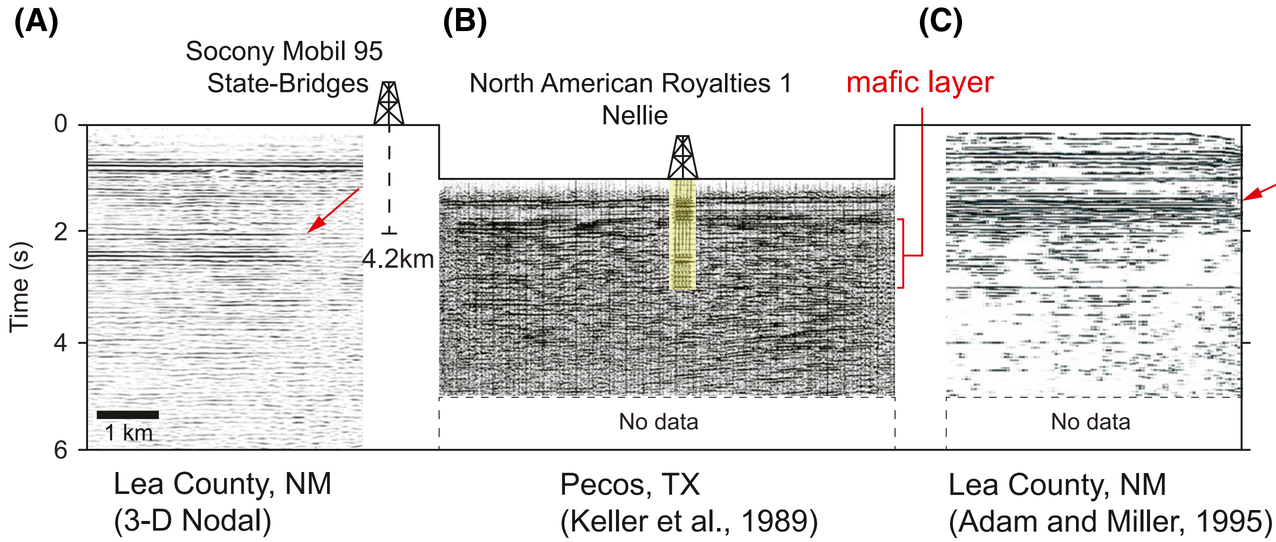

Figure 5. (A) Two-dimensional common reflection point stacked section extracted from the three-dimensional (3-D) data volume produced in this study (southeastern New Mexico [NM]) compared with (B) a reflection section from southwestern Texas (TX) (Keller et al., 1989) and (C) a seismic section from eastern NM reported by Adams and Miller (1995). The North American Royalties 1 Nellie well (see Figure 2B) is shown in (B) along with synthetic seismograms derived from the well logs (Adams and Miller, 1995). Note that the Pecos section (B) has been shifted 1.2 s downward to account for relatively thicker sediments in Lea County (A). The red arrows in (A) and (C) indicate prominent reflections, here interpreted as igneous intrusions.

southern Illinois to detail structure associated with these reflectors. A recent 3-D seismic survey of the Fennoscandia basement reflections (Hedin et al., 2016) has further strengthened the argument that mafic sills are a likely cause of similar appearing layered basement reflectivity.

Although the presence of similar reflections on these reprocessed nodal data from southeastern New Mexico expands the known extent of such layering, the data set is too small to provide unequivocal evidence to discriminate between these interpretations (see the following section). However, it does draw fresh attention to the observations from the only well known to penetrate similar reflectivity observed in the region, the North American Royalties (NAR) 1 Nellie (Figure 2B). As first presented by Keller et al. (1989), the NAR 1 Nellie encountered an ultramafic layered intrusion, a part of the Pecos igneous suite, at the depths corresponding to the first series of strong basement reflections beneath the nearby seismic line (Pecos, Figure 5B). The Nellie intrusion is reported to be a thick (1.4 to 5.8 km [4593 to 19,029 ft] at depth) mafic to ultramafic layered intrusion with a radiometric age of circa 1163 Ma (Kargi and Barnes, 1995). Keller et al. (1989) conjectured these reflections to be a manifestation of Keweenawan rifting of the midcontinent (ca. 1.1 Ga). Adams and Miller (1995) also argued from the NAR 1 Nellie results a similar interpretation of layered reflections on their seismic profile from eastern New Mexico (Figure 5C), not far from the nodal survey reported here. Both New Mexico lines lie approximately 50 km (~31 mi) away from the well (Figure 2B).

If, as suggested by the NAR 1 Nellie, the extensive layered sequences in the United States midcontinent are correlative and the result of Keweenawan magmatism, it would imply an igneous intrusion event over a much greater expanse of the eastern United States than generally realized (Figure 2A). Although such a sequence of related sills (whether Keweenawan or GRP related) over such a vast area may seem extraordinary, we point out that similar sill-like basement reflectors found on several LITHOPROBE seismic lines in the Trans-Hudson orogen (e.g., Mandler and Clowes, 1997) have been linked to the Mackenzie dikes swarm, which has been mapped over a comparably large area (Figure 2A).

New Insight from Three-Dimensional Imagery

The nodal data do provide new 3-D imagery with which to evaluate the various hypotheses for the nature of this basement layering. The advantages of 3-D over 2-D seismic surveys are well known in the exploration industry, both in terms of accurate imaging as well as interpretation (Brown, 1986). Because 3-D imagery has largely been lacking for continental basement, its full value in the latter context remains to be explored. First, we note that the interval velocities for these basement strata obtained from stacking velocities (Figure 3E; e.g., Oliver et al., 1976) are relatively high (6.0–6.5 km/s [19,685–21,325.5 ft/s]) for most sedimentary rocks but are consistent with igneous or metamorphic materials. However, such average velocities do not preclude a depositional (volcanic or clastic) component, especially if substantial limestone is present, nor even the possibility that they may contain hydrocarbons. Here, our focus is on geometrical features within the data volume in an attempt to identify possible structural discriminants of intrusive versus depositional activity.

Figure 6 shows a 3-D seismic reflection cube for traveltimes from 0–6 s and two seismic time slices from the data cube. This corresponds to the upper part of the Precambrian layering. The linear feature exhibited in Figure 6B could be the expression of igneous dikes, a vertical feature that might be difficult to distinguish on any 2-D basement reflection imagery. Circular features in the upper basement depth slices might also be interpreted as intrusive elements (e.g., pipes, plutons, laccoliths, etc.; Figure 6C). The circular feature in Figure 7 exhibits a successively decreasing radius with increasing traveltime (depth) that implies a cuspate geometry. The sag of this cuspate geometry is subtle in cross-sectional views of our seismic profiles but is clear in the 3-D time slices. Saucer-shaped reflections in both Phanerozoic strata and basement rocks observed on industry and academic seismic surveys elsewhere have been either identified or interpreted as mafic igneous intrusions (e.g., Hansen and Cartwright, 2006; Polteau et al., 2008). McBride and Kolata (1999) and McBride et al. (2016) found a larger scale cuspate geometry associated with the basement reflectivity in central Illinois, which they likewise attribute to mafic intrusion. Neither of these particular patterns is unique to igneous processes. Linear patterns are common in sedimentary sequences because of faulting, and a cuspate geometry could just as easily be evidence of a sag in a sedimentary (or now metasedimentary) basin or even velocity pulldown. Such ambiguities notwithstanding, 3-D coverage of a significantly larger area is likely to provide more definitive clues of structural relationships that might help distinguish between depositional and intrusive origins. Three-dimensional basement imagery is certainly

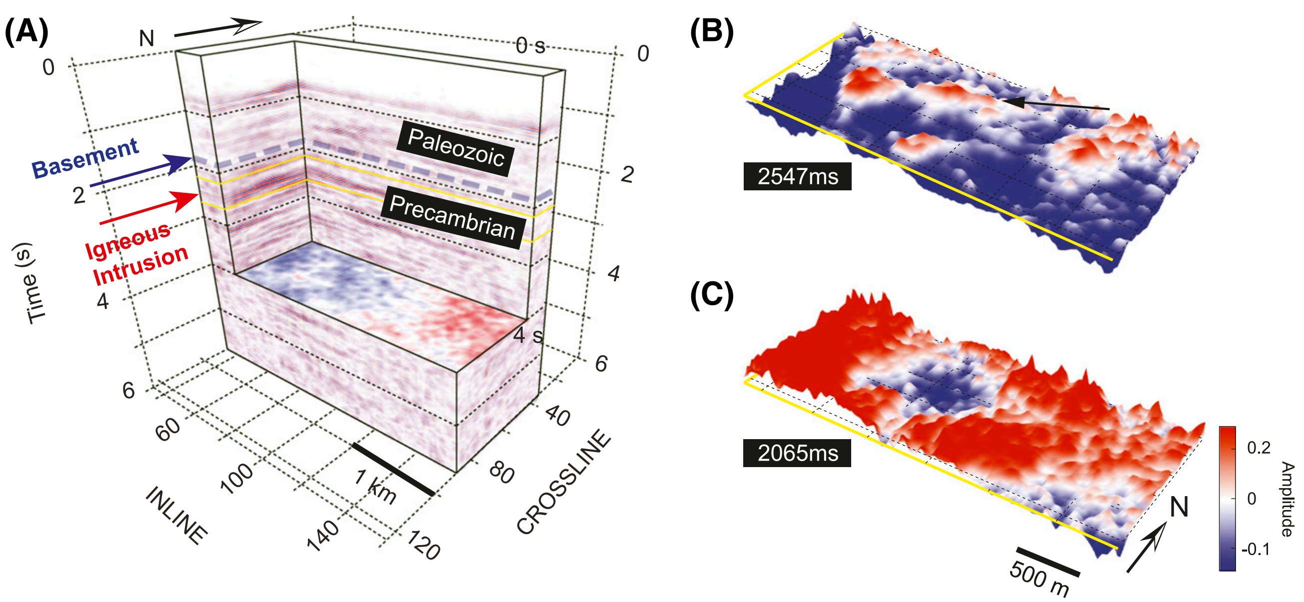

Figure 6. (A) A three-dimensional seismic reflection volume of the basement produced in this study. The blue arrow indicates the top of the Precambrian basement as reported from a drill hole near the survey. The red arrow indicates one of the prominent reflectors, here interpreted as igneous intrusive layering within the basement. (B, C) Seismic time slices with amplitude depicted as pseudotopography, illustrating circular and linear features discussed in the text.

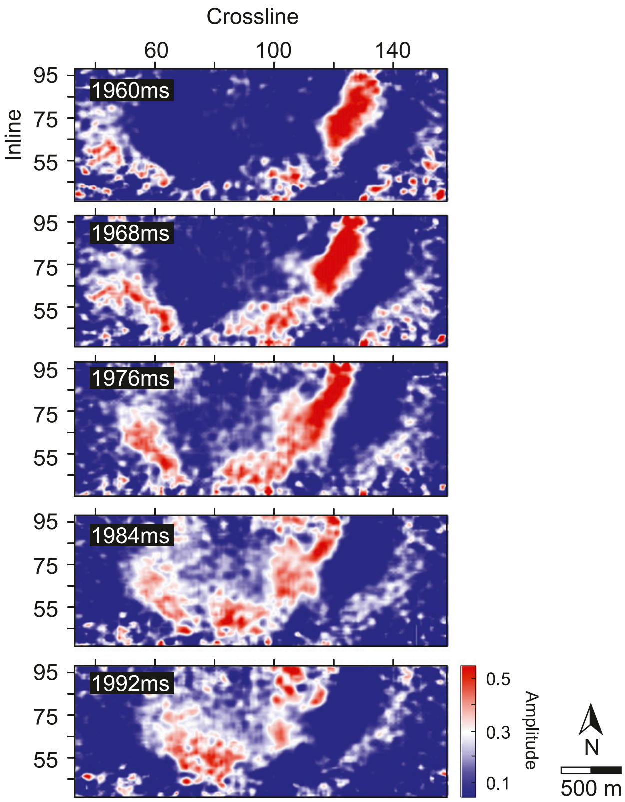

Figure 7. A series of seismic time slices for traveltimes 1.96–1.99 s extracted from three-dimensional reflection data volume produced in this study. The shrinking ovoid pattern suggests a saucer-shaped reflector.

amenable to more sophisticated analytical processing (e.g., continuity extraction, attribute mapping, etc.) designed to extract maximum information from both amplitude and geometrical relationships (e.g., Hedin et al., 2016; McBride et al., 2018). The nature and extent of this demonstration data set was judged too limited to warrant such analysis at this time.

We hasten to point out that such data exist within the nodal surveys already collected in the Permian Basin but are not yet available for analysis. Advanced processing, beyond the scope of this report, could be very effective for the analysis of this larger data volume from which this sample was extracted. This report is intended to encourage such analysis, not only for the Permian Basin but for all nodal surveys collected during routine oil exploration activities.

Relevance to Oil and Gas Exploration

The structure and evolution of the basement imaged by such data as examined here is of more than academic interest. Sedimentary basins and their internal structures (and resources) are commonly linked to underlying basement tectonics. In a more recent context, basement faults are suspected to be a major factor in defining the hazards related to seismicity linked to waste water injection by the oil and gas industry (e.g., Ellsworth 2013; Keranen et al., 2014). Knowledge of the geometry and distribution of basement faults in areas of water injection would aid in mitigating any hazards associated with such injection (e.g., Horton, 2012; Kim, 2013). On a related note, McBride et al. (2018) suggest that microseismicity associated with CO_2 injection in central Illinois is controlled by basement fracture mapped by their 3-D seismic imagery of the basement.

CONCLUSIONS

Here, we demonstrate how 3-D seismic reflection data collected by modern, continuously recording systems can provide a valuable byproduct by processing normally discarded portions of the recordings. Using extended correlation of petroleum seismic surveys from the northern Permian Delaware Basin in southeastern New Mexico, we have produced a 3-D seismic volume detailing basement layering that we proposed to be part of an extensive Precambrian sequence found by seismic surveys throughout the central United States. Although the origin of this layering is still debatable, dated samples from the only borehole to penetrate similarly appearing seismic layering suggest that it is because of mafic material emplaced during the Keweenawan rifting of the midcontinent. The great extent of magmatism implied by this interpretation (from west Texas to Ohio) is not unreasonable given the known extent of magmatism associated with similar igneous events, such as the Mackenzie dike swarms of Canada.

Although the quality of the deeper imaging obtained is inferior to that from a dedicated deep reflection survey, it is more than adequate to address important geologic issues of both academic and practical significance. The imagery is truly 3-D, allowing identification of features that are commonly unrecognizably subtle in 2-D profiles. Such information is central to understanding the evolution of the continental basement in general and to specific energy-related issues such as seismic risk associated with fluid injection near basement faults.

The most significant conclusion from this study is that modern, nodal, continuously recorded industry surveys are routinely and serendipitously collecting important 3-D seismic imagery to intrabasement depths. This already extensive and growing volume of deep-crustal information should be examined and certainly should not be discarded. It has the potential to transform our understanding of continental structure and tectonics to the same degree that 3-D seismic surveying has revolutionized the resource exploration industry itself.

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