NEAR-SURFACE SEISMIC IMAGING USING FIRST ARRIVAL TIME INVERSION WITH PRE-STACK DEPTH MIGRATION

By

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NEAR-SURFACE SEISMIC IMAGING USING FIRST ARRIVAL TIME INVERSION WITH PRE-STACK DEPTH MIGRATION

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1. Abstract

This paper presents a hybrid acquisition strategy for imaging near surface stratigraphy. Shallow seismic depth imaging studies typically involve data processing followed by velocity estimation and migration. Most researchers apply the commonly used conventional processing (stacking velocity analysis) for velocity model building that in turn is used in migration. However, we find that when it comes to shallow imaging, the conventional processing lacks accuracy in velocity model estimation, which consequently leads to poor quality in depth image. To improve the velocity model reliability, we followed an unconventional procedure: first arrival inversion combined with prestack Kirchhoff depth migration. We demonstrate the imaging application for an ultra shallow (<15m) geological target, which is a set of paleo-channels in the Bull Creek, Beaver

County, Oklahoma. To demonstrate the concept two coincident profiles were acquired – one targeted towards inversion and the other towards migration. Besides migrating data with the inversion model, we also migrate the data with velocity model developed though conventional processing. We compare the results to illustrate that significant improvements can be made in imaging of the shallow subsurface by using velocity models created by traveltime inversion.

2. Introduction

The multi-channel[1] seismic method, conventionally used to image features at crustal (>10 km) or basin (0.5 – 10 km) scale, is now gaining popularity with researchers working in the onshore near-surface (< 0.5 km). For example, Hunter et al. (1984) imaged shallow overburden-bedrock interface (< 0.2 km) in three localities - Kitmat, British Colombia; Quyon, Quebec; and Shawville, Quebec using a 12-channel seismometer and Jeng (1995) performed a shallow seismic reflection experiment (< 0.1km) to investigate an urban construction site where the shallow structure consists of a thin top layer of sandy soil overlying a sequence of inter-layered sand and gravel. The intrinsic advantage working in the near-surface is the preservation of higher (> 100 Hz) frequencies. Thus, the same processing flow that is applicable to basin or crustal scale investigations – common mid-point stacking followed by post-stack migration (Grau and Lailly, 1993) – may yield higher spatial resolution in the near surface. For example, Juhlin (1995) conventionally processed a land dataset and retained the 90-270 Hz frequency bandwidth to image a fracture zone from 100 to 400 m in depth with a vertical

[1] Multiple receivers simultaneously records energy from a single shot

resolution of nearly 10 meters in Finnsjon, Sweden. Miller et al. (1995) processed land data to preserve a dominant frequency of ~200 Hz when delineating stratigraphy relevant to hydrologic modeling of unconsolidated sediments within the top 60 m at Cherry Point Marine Air Base, North Carolina.

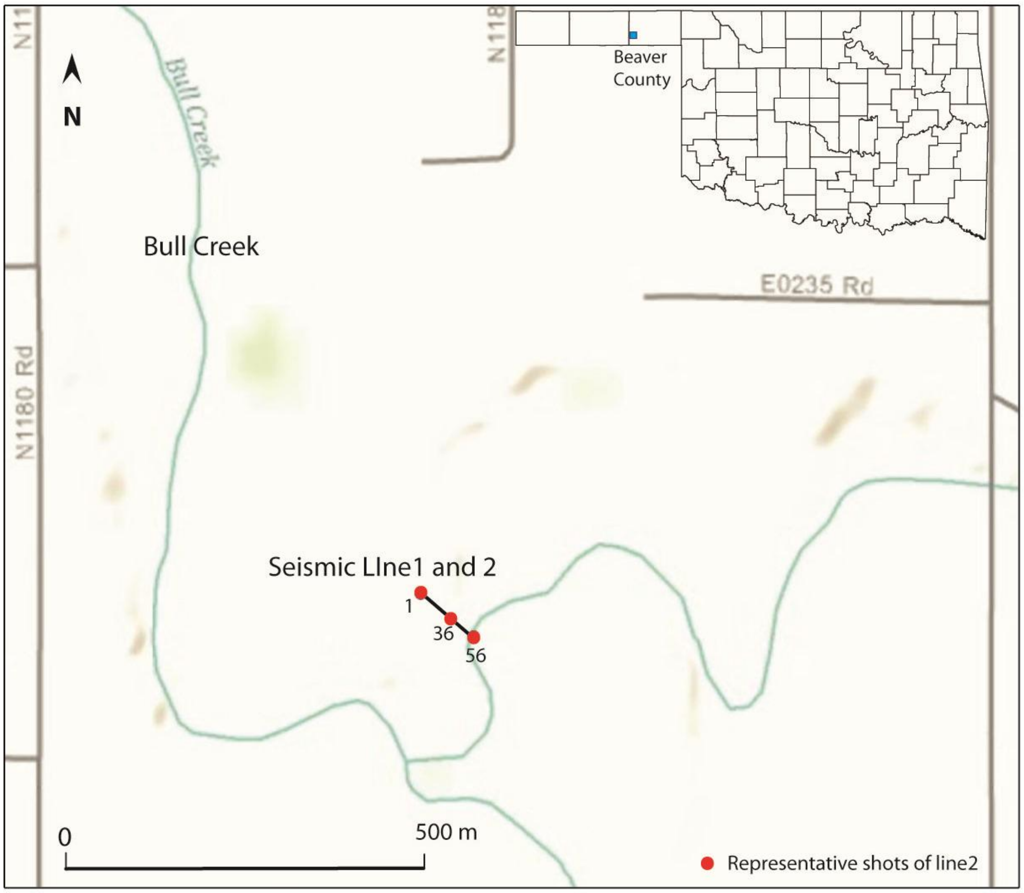

Figure 1: Study area. The drainage system is labeled. Location of seismic profiles Line1 and 2 are shown as a solid line. A representative shot gather from the middle of the line is shown in Figure 2. Location of the Beaver County with respect to the state of Oklahoma is shown in the inset.

A significant disadvantage of working in the near-surface is the overwhelming presence of ground roll and air waves generated in the upper unconsolidated sediments that tend to mask reflection events (Jeng, 1995; Bachrach and Nur, 1998; Ivanov et al., 1998; Steeples, 1998; Steeples and Miller, 1998; Bradford et al., 2006). If using the same source-offset range while working deeper in the near-surface realm, due to the wider aperture of reflections in a CMP bin as compared to that in a basin or crustal scale acquisition, the hyperbolic ray trajectory assumption in the CMP domain may be significantly violated (Grau, 1993; Grau and Lailly, 1993), while lateral velocity changes in the weathered zone may further intensify the problem.

General advancement in processing such as pre-stack depth migration (PSDM) has greatly improved attempts to circumvent conventional processing and obtain reasonable results with limited coda in the reflection window (Grau and Lailly, 1993; Pasasa et al., 1998; Bradford et al., 2006). Pasasa et al. (1998) applied PSDM based on the Kirchhoff algorithm (Schneider, 1978) and successfully imaged shallow interfaces of an underground building buried in a waste disposal site. Bradford et al. (2006) showed the benefits of using PSDM over post-stack time migration using data from Alvord Basin, Oregon to image faults at a depth of 0.025-1 km. On similar lines, Garu (1993) showed the advantages of PSDM in imaging stratigraphy with strong lateral variation. However, it is commonly accepted that velocity model building for PSDM prestack is a meticulous exercise due to the sensitivity of the migration in the pre-stack domain to velocity (Grau and Lailly, 1993; Grau, 1993; Pasasa et al., 1998; Begat et al., 2004).

Adequacy of a velocity model for PSDM depends on its smoothness and its ability to represent the large scale features of the subsurface (Yilmaz, 1987; Black et al., 1994). Typically, velocity models for PSDM are based on stacking velocity models generated in the CMP domain. However, due to a scatter in coherency typically observed in the near surface stacking, models are prone to subjectivity. Traveltime inversion, a

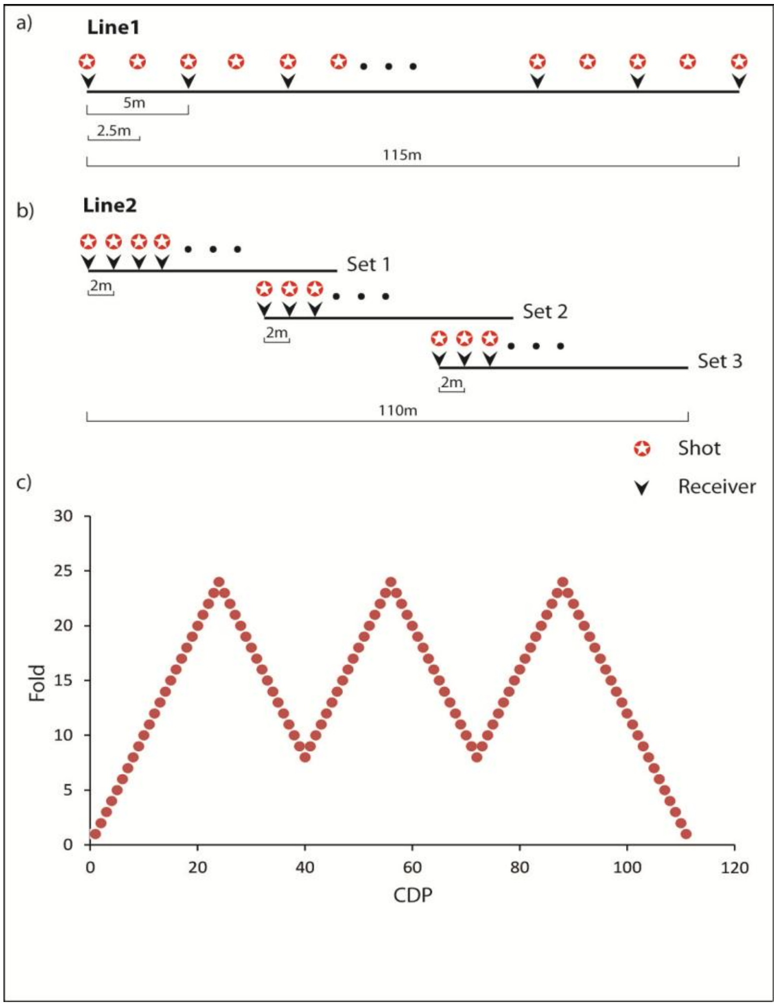

Figure 2: Acquisition layouts and stacking chart

model-based method of estimating medium properties (P-wave velocities in this paper), is an objective alternative to estimate reasonable velocity models for PSDM (Lailly and Sinoquet, 1996; Le Begat et al., 2004; Jaiswal and Zelt 2008). Although traveltime inversion is a ray-based method that is theoretically limited in its resolution capabilities, it has been used for exploration at different scales. Carrion (1991) and Dell'Aversana et al. (2003) inverted large offset reflections (~10 and ~18 km maximum offsets, respectively) in thrust belt settings and imaged structures that were poorly imaged with conventional processing. Zelt et al. (2006a) inverted first-arrival times to build a velocity model of the very shallow subsurface (~15 m) and ground truthed it with borehole data. Flecha et al. (2004) have even estimated low-velocity zones using first-arrival inversion of 2-D seismic data. Although their estimation was qualitative in nature, it had practical uses for the interpretation of the geology.

The velocity model from traveltime inversion can be reasonable for the following reasons. First, traveltime inversion honors the physics of wave propagation. Second, the data for traveltime inversion, i.e., the arrival times of direct and reflected events, can be weighted according to the confidence with which they are identified in the data, thus reducing the effect of noise. Third, traveltime inversion can be regularized such that the large-scale geological features are first imaged followed by the smaller-scale features. The extent of the resolution is set by the uncertainties in the traveltime picking. In this paper, we present a case study on how a reliable velocity model can be estimated from first arrival inversion, instead of the conventional processing, and be used as an input in prestack depth migration to generate a geologically sensible depth image.

3. Study area and acquisition

The study area is located within the central part of the Bull Creek drainage system of Beaver County, Oklahoma (Figure 1). This drainage system is a18 km long ephemeral tributary of the Beaver River that is underlain by Permian and Miocene bedrock (Carter and Bement 2004; Bement et al., 2007). A series of fluvial terraces within the Bull Creek valley was created by multiple episodes of local incision into the regional plains. Terraces within this drainage system are composed of late-Pleistocene and Holocene sediments

(Bement et al., 2007), discontinuous along the length of the valley, and vegetated.

Bull Creek has also become of interest for paleo-environmental reconstruction, archeology and bio-stratigraphy (Totten, 1956; Bement et al., 2007). Three types of strata, alluvium, colluvium and eolian deposits, ranging in age from late-Pleistocene to early Holocene are exposed in the fluvial terrace deposits of the Bull Creek Drainage and have been used in reconstructing the paleo-environment history of the area (Carter and Bement, 2004; Bement et al., 2007). The purpose of the seismic imaging in this paper is to better understand the evolution of these fluvial channels and terraces and confirm the cross-cutting relationships among them. With our instrumentation (next section) we attempt to image the contacts between the weathered, unconsolidated, deposits that comprise the Holocene and late-Pleistocene sediments and the underlying compact Permian Cloudchief Formation, composed primarily of red clay shales, very fine-grained sandstones, and siltstones.

The 2-D seismic profiles are acquired on the western side of Bull Creek with an azimuth of N120^{0}W (Figure 1). The acquisition instrumentation comprised a Geometrics Geode recording unit and a set of 48 14.5 Hz vertical component geophones. An 11-pound sledge hammer served as the seismic source. Although our initial intension was to use all 48 channels due to equipment failure only 24 channels could be used. Data were acquired to address two purposes in this paper – first, to generate a velocity model for depth imaging and second, to generate a reliable depth image. To serve the purposes we acquired two independent coincident profiles. The first profile, hereafter referred to as Line 1, was meant for first arrival inversion and was acquired with a wider aperture (~50 m maximum source-receiver offset and 2.5m bin spacing; Figure 2a). The choice of maximum offsets was based on target depth (up to 15m) and it was assumed that the stratigraphy is sediment dominated with velocities linearly increasing in depth. The second profile, hereafter referred to as Line 2, was meant for migration and was acquired with a denser bin spacing (1m bin spacing and ~20m maximum source-receiver offset; Figure 2b). The choice of the bin size was to enable adequate sampling of the smallest anticipated wavelength of 4 m (assuming an average velocity of 750 m/s and a dominant frequency of 125Hz). Both Lines 1 and 2 were acquired in a split-spread style. Along Lines 1 and 2 at every shot location five hammer strikes were summed together to suppress random noise. The data were recorded for 1 second with 0.5 ms sampling interval. Line 1 and Line 2 are 110m and 115 m long respectively and the variations in topography along the seismic lines are 6.2m for Line1 and 5.2m for Line2.

Line 1 comprises 47 shots. Receivers along Line1 were placed uniformly at 5m and recorded arrivals from every shot that were fired at 2.5m spacing. Line2 was acquired in three segments to maintain a desired bin size of 1m for migration; consecutive segments are overlapped by 8 geophones. While processing, the three segments were merged to generate a single dataset. As a result, the fold of Line2 is uneven (Figure 2c). Although 72 individual shots were fired along Line2, 16 shots were coincident. Therefore for processing, data were reorganized into 56 shot gathers after merging the three segments. While merging, the coincident shot traces with the same offsets were stacked (Figure 2d). In general, data were contaminated with low-frequency and high amplitude coherent events. Figure 3 (a, c & e) shows the three representative shot gathers from Line1. These noise trains mask the reflections in the near offset (< 10 m shot-receiver offset). Although the noise could be dispersive in nature (velocity appears to be changing with frequency), our processing assumed otherwise. We anticipate that a proportion of the noise could also be due to reverberations of the strike plate. The noise is predominantly treated as air waves and ground roll.

4. Methods

The methods in this paper are geared towards depth imaging the top 15m of the subsurface where a channel system is anticipated. Depth imaging of multichannel seismic data is a two-step process in practice wherein a velocity model that describes the large-wavelength characteristics of the subsurface is first constructed and then used for depth migration to estimate the small-wavelength subsurface features (Gray et al., 2001). The large wavelength model of the subsurface is estimated by inverting first arrivals identified in Line1 data using the regularized inversion algorithm of Zelt and Barton (1998) and the model is used to depth migrate data from Line2 in prestack common-offset domain using the Kirchhoff method (Schneider 1979). Picking, processing and depth imaging are done using the commercial software ProMAX.

Traveltimes in the regularized Zelt and Barton (1998) method are computed by solving the Eikonal equation on a regular grid using Vidale's (1988) finite-difference method modified to account for large velocity gradients (Hole and Zelt, 1995). Raypaths are determined by following the steepest gradient of the time field from a receiver to a source based on Fermat's principle. The traveltime problem is nonlinear in the sense that both the raypaths and the velocity field are interdependent and unknown at the outset. The problem is linearized by assuming only one unknown at a given time. It is implemented using a known velocity model (m), also known as the starting model, which is iteratively updated based on the difference between the observed traveltimes (t_0) and the traveltimes predicted with the known model (t_p). The iterations are continued untill the difference between t_0 and t_p is reduced to within picking uncertainties (u). Picking uncertainties are chosen based on the dominant frequency with the assumption that the errors in the observed picks are uncorrelated and Gaussian in nature.

The inverse modeling is an automated way of computing the updates required in the starting model. An objective function (Φ), which is the $L2$-norm of a combination of data errors ($\delta d = t_0 - t_p$) and model roughness (second-order partial derivative; Lees and Crosson, 1989) is minimized to compute the model updates:

$$\Phi (m) = \delta t^T C_d^{-1} \delta t + \lambda \, [m^T C_h^{-1} m + s_z m^T C_v^{-1} m] \quad (1)$$

In Equation 1, C_d is the data covariance matrix; C_h and C_v are the horizontal and vertical roughening matrices, respectively; λ is the trade-off parameter; and s_z determines the relative importance of maintaining vertical verses horizontal model smoothness. The regularization, implemented by scaling with the inverses of the data and model space covariance matrices, attempts to obtain the smoothest model appropriate for the data errors (Scales et al. 1990). The data misfit in traveltime inversion is assessed using the normalized form of a misfit parameter referred to as the chi-squared (χ^2) error (Zelt, 1999):

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{t_p^i - t_o^i}{u^i} \right)^2 \quad (2)$$

In Equation 2, n is the number of traveltime picks. A unity in value of χ^2 indicates that the observed traveltimes have been fitted at their uncertainty levels and the inverse problem is considered to have been converged to an acceptable solution, i.e. a final model. As in any linearized inverse problem, the final model is influenced by the starting model. Our goal in this paper is to seek a model which is least influenced by any existing interpretation. Further, we seek a model which is smooth and has only those features that are required by the traveltime data as opposed to being merely consistent with them. To keep our modeling objective we chose a starting model which has no lateral velocity structure. The vertical velocity structure is only reflective of a general near-surface stratigraphy. Based on general data quality and the dominant frequency we assign an overall uncertainty of 4ms to all traveltime picks. Further, in this paper, achieving a value of unity for χ^2 is a necessary but on a sufficient criterion; the geological sensibility of the evolving model through successive iterations plays an equally important role.

Following the velocity-depth model estimation, prestack Kirchhoff depth migration (PSDM) utilizes the updated velocity model as an input to produce the final depth image. Kirchhoff migration migrate data based on the Kirchhoff summation: the summation of amplitude along hyperbolic paths that incorporates the obliquity, spherical spreading and wavelet shaping factors (Yilmaz, 2001). The PSDM migrates the data in common-offset domain from the topography by applying a Green's function to each CDP location using a traveltime map. The traveltime map relates the time from each surface location to a region of points in the subsurface and is computed by Implicit Eikonal Solve. The accuracy of the velocity model is highly essential in acquiring a reliable depth migrated image.

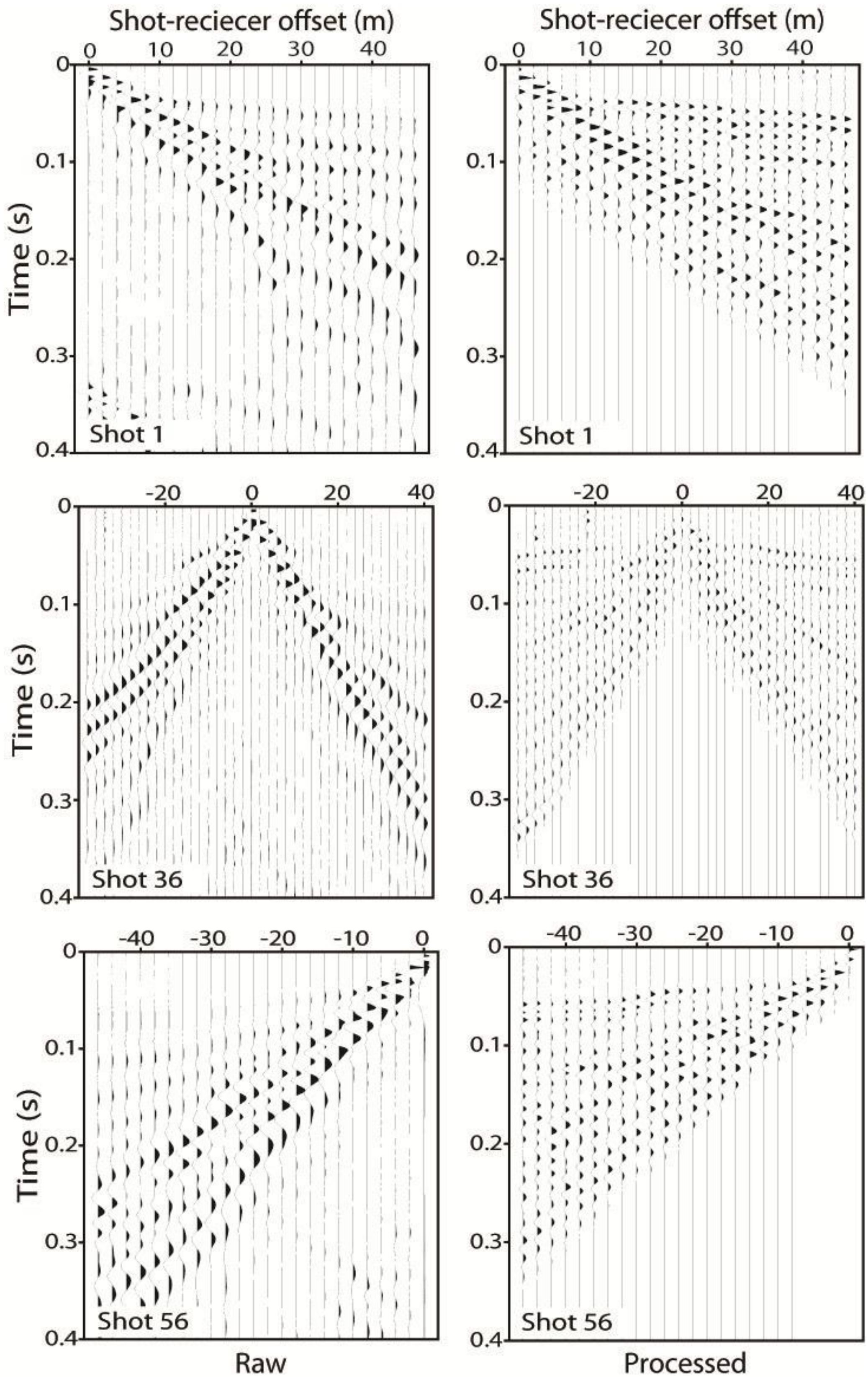

Figure 3: Representative shot gathers 1, 36 & 56: (a, c & e) raw and (b, d & f) processed

5. Application and results

Line1 data, used for traveltime inversion, were minimally processed so as to avoid any phase shifts in the data. First arrivals could be identified to the farthest offsets in all shot gathers. In the near offsets (< 4 m) the first arrivals were masked by noise and had to be carefully identified. In a few gathers no picks could be made at the near offsets. In the end, 1058 first arrival-times are picked from a total of 47 shot gathers along the seismic line. A number of layered-earth models were used as starting model; a model with velocity of 300m/s at the topography linearly increasing to 1500 m/s at 30 m depth emerged as the best starting model. With this starting model χ^2 error monotonically decreased and the inverse problem converged in 12 iterations. The resulting final model (Figure 4a) appears to have a reasonably uniform ray coverage. It is used for depth migrating data from Line2.

Line2 data, used for migration, were moderately processed in an attempt to preserve as much of the relative amplitude as possible. The processing mainly comprised of filtering and an air-blast attenuation. A 40-80-100-200Hz Ormsby bandpass filter appeared to have best cleaned the data. Following the band-pass filter, applying an air blast attenuation further improves reflections with ~10m offsets (Figure 3b, d & f). Line2 data at this stage are ready for migration with the traveltime inversion model. A velocity field was extracted from the inverted model prior to PSDM such that the model topography agrees with the acquisition topography.

Simultaneously, we adopted a second path to develop a velocity model through stacking velocity analysis. For this, first, datuming and static corrections are performed. We use pre-stack wave-equation datuming (Berryhill 1984) with traveltime inversion

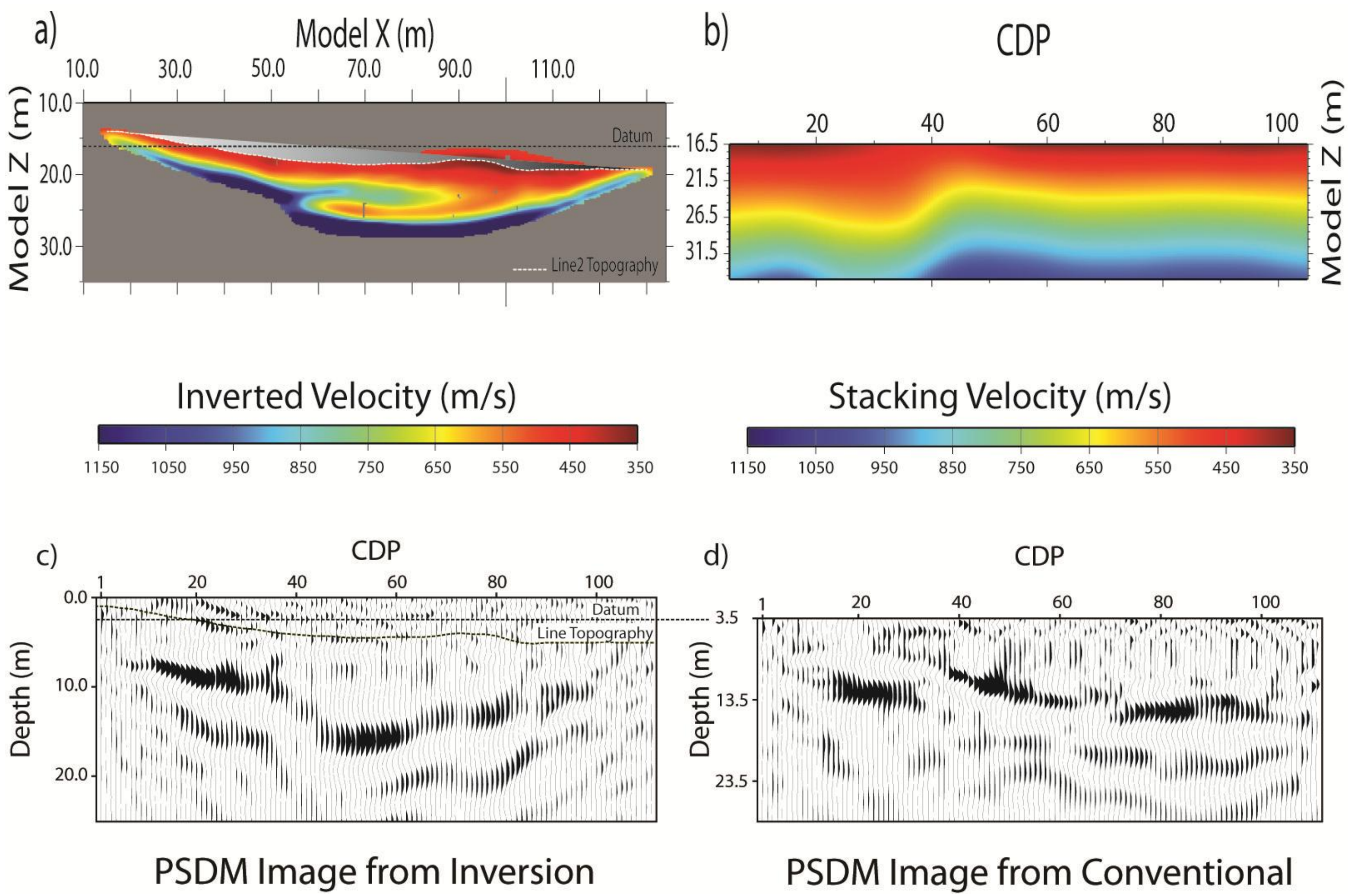

Figure 4: (a) Inverted velocity model. (b) Processed velocity model. (c) Depth image from Inversion. (d) Depth image from Processing.

velocities (Figure 4a). The datum for stacking velocity analysis is considered at an elevation of 784.17m above mean sea level; the minimum and maximum elevations along Line2 are 781.17m and 786.70m respectively. The stacking velocity analysis is done using the semblance method (Yilmaz 2001). The data yielded a scattered semblance plot and it was difficult to obtain a reasonable constraint on the stacking velocities. The semblances were either wide spread or had a shot-gun appearance. In a trial-and-error manner, we generated a number of stacking velocity models which were transformed to their interval velocity counterparts through the Dix method (Dix, 1955) and were used for PSDM. For PSDM, data are sorted in common offset domain and binned at an increment of 4m. The common-offset bins are padded to guarantee each bin contains at least one trace per CDP. Two separate PSDM applications are made – the first, with velocity model obtain through traveltime inversion (Figure 4a) and the second, with a velocity model estimated from stacking velocity analysis (Figure 4b). PSDM with inverted model is performed from the topography (Figure 4c) while PSDM with the processing model is performed from an arbitrary flat datum which roughly averages the topography (Figure 4d). In both cases a maximum of 120 Hz is migrated.

The PSDM image with the inverted model (Figure 4a), in general, appears to provide the most detail and shows the best migrated depth image. Three bright reflections (red, green, and blue; Figure 5) located between CDPs 1 and 34 and 1-9 m depth; between CDPs 34 and 75 and 9-16 m depth; and between CDPs 89 and 110 and 5.2-9 m depth are recognized and interpreted as three different terraces based on their reflection strength, continuity and the geological setting. The topography in Image1 starts at CDP 1 at the top of the model and ends at 5.2 m model depth at CDP 110. Incoherent reflections visible above the topography are processing artifacts that are likely generated as the first arrivals were not explicitly muted for migration (PSDM separates the reflections from the turning

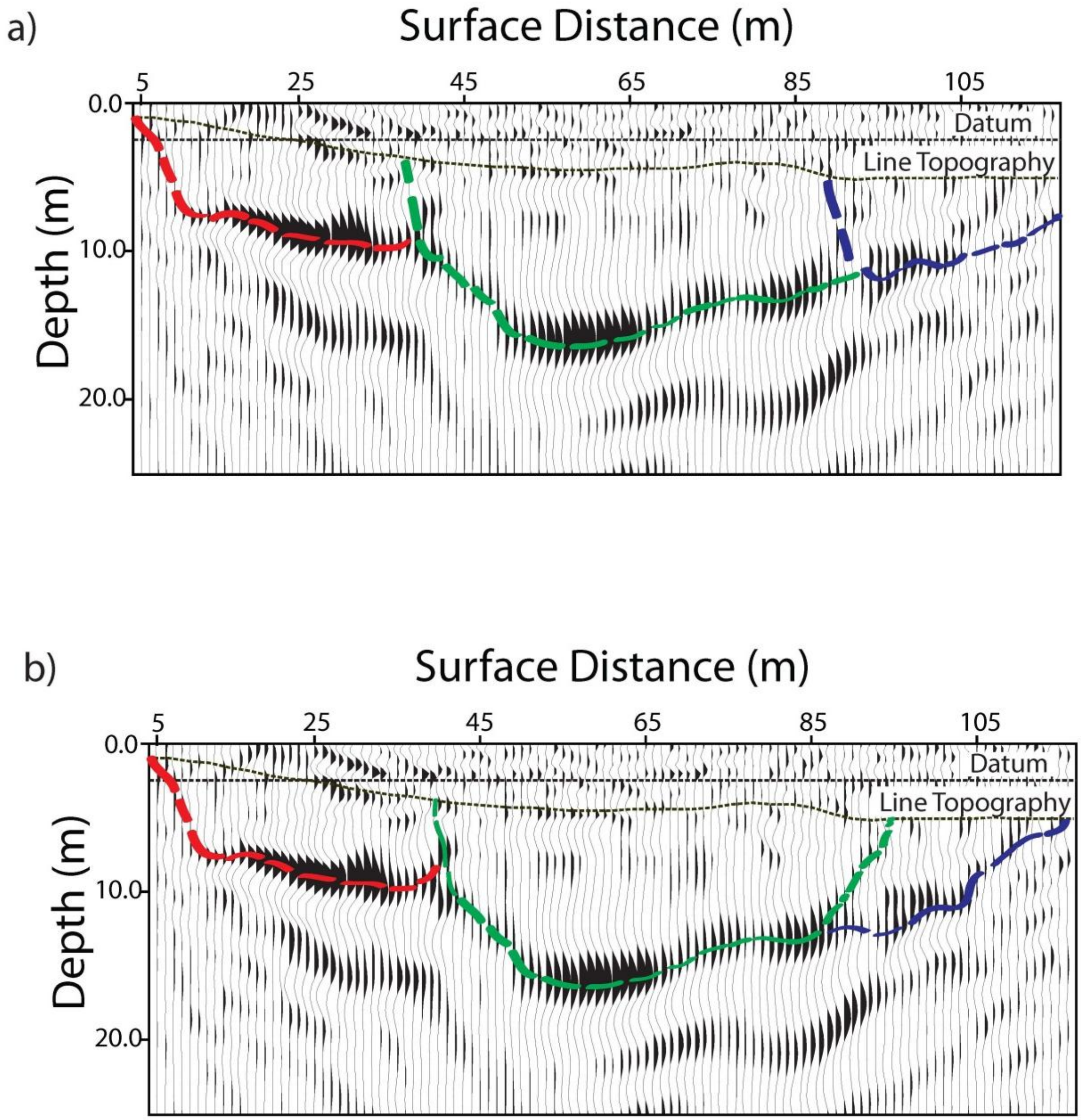

Figure 5: Same as Figure (4c), with two different interpretations (a) & (b). The red, green, and blue lines indicate the position of three inset terraces. We provided their ages

based on mapping and correlation with dated deposits.

rays). Deeper reflections in parts of the velocity model, which have no ray coverage, are unreliable. They were migrated using an unconstrained velocity field that is merely a downward extrapolation of parts of the velocity model that have ray coverage.

6. Discussion

6.1 Geologic Interpretation

Figure 6 illustrates the outline of mapped terraces based on topographic surveys of the Bull Creek valley in the location of the seismic line. The interpretation made from the seismic survey corresponds well with the three terraces (T1, T2 and T5) identified during mapping. Channel incision has exposed profiles of the sedimentary deposits composing these terraces. The deposits consist mainly of alternating coarse fluvial channel deposits and overbank deposits interbedded with paleosols. Radiocarbon ages were obtained from the total organic carbon fraction of several of these buried A-horizons (Conley, 2010). The ages of the deposits within the exposed profiles suggest that the floodplain deposits comprising T5 were deposited between 13,210 ± 80 and 6,200 ± 90 RCYBP. Rapid down-cutting ensued, followed by the deposition of T2 material between 3,470 ± 40 and 2,540 +/- 40 RCYBP. Deposition of T1 occurred after 2,540 ± 40 RCYBP. Our seismic image illustrates this history very well (Figure 4a). This geologic history is not unique to the Bull Creek drainage but is found throughout the geologic record. Many model-based cartoons have been produced throughout the literature illustrating the cross-cutting relationships amongst these terrace units (e.g. Blum et al., 1994-GSA Bulletin 106: 1002-1016). In addition, very similar geometries have been documented in offshore seismic profiles that were interpreted to represent nested fluvial terraces (e.g. Thomas and Anderson, 1994; in Incised Valley Systems: Origins and Sedimentary Sequences, SEPM Spec. Pub. 51), but to our knowledge this is the first study to provide a seismic image of the cross-cutting relationship among a confirmed set of inset fluvial terraces. Figure 7 illustrates the geologic model with respect to age of deposition.

6.2 Implications for Seismic Imaging

Using velocity models from inverse methods for PSDM can have several advantages over estimating velocity through processing. First, topography can be better accounted for. Second, traveltime inversion can be regularized such that large-scale geologic features are imaged first, followed by the smaller-scale features. Third, model resolution is noise dependent. Poorly resolved parts of the model may not migrate the data adequately, which can be honored in interpretation. Fourth, depending on the ray coverage it can predict which parts of the model may not be suitable for interpretation. For example although Image1 shows coherent reflectors even in the deepest parts of the image, the ray coverage can be used to decide which reflections may be spurious.

PSDM with inverse model (Figure 4c) in general appears to be better suited for interpretation due to a high coherency of the reflection events. Although both images appear to have high amplitudes within the depth of 16 meters, Image1 better fits the expected channel morphology both vertically and laterally.

Although processing in this paper has suppressed near offset noise, wide reflection apertures and strong velocity gradients may have limited the ability of conventional processing (Grau and Lailly, 1993; Pasasa et al., 1998). Further, stacking velocity analysis is like a moving average with a window length equal to the spread.

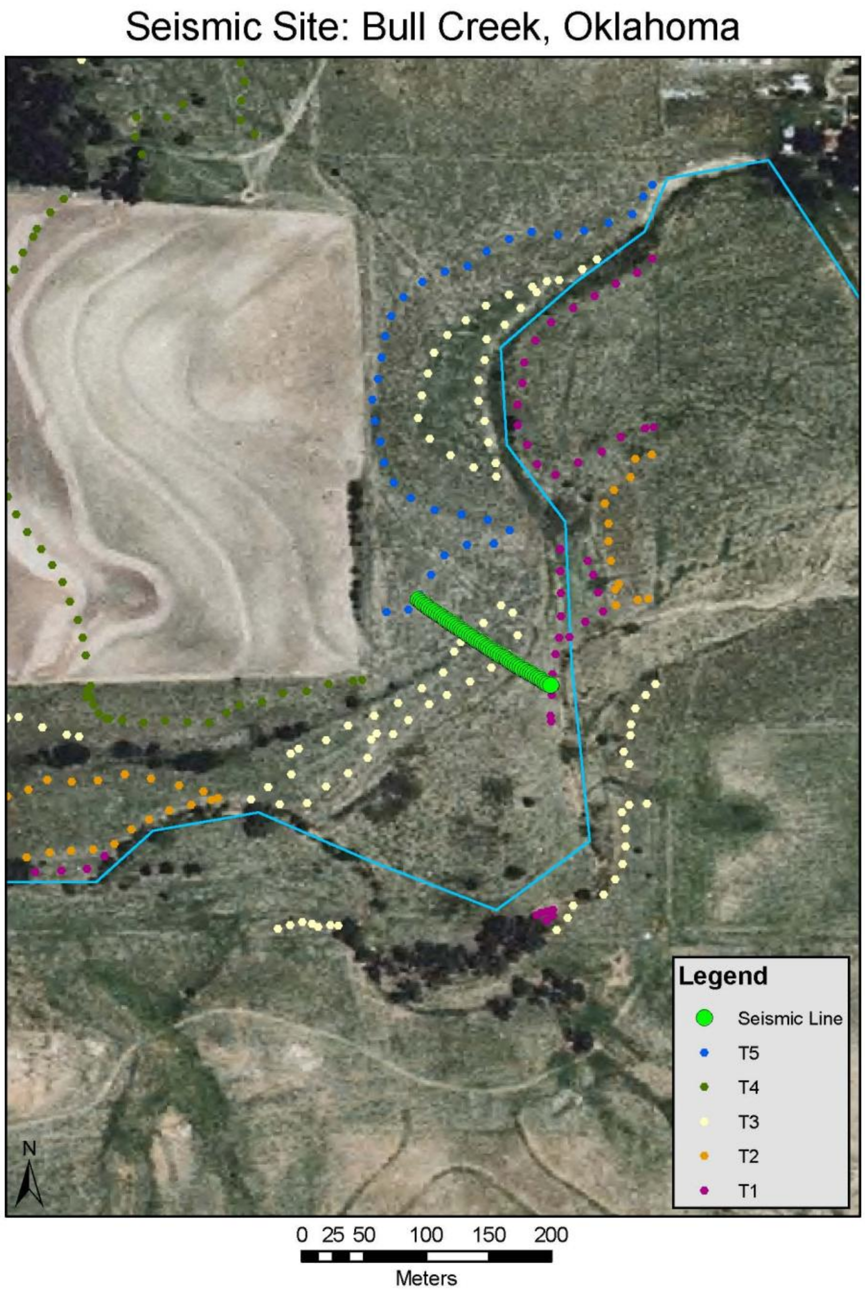

Figure 6: Regional surface mapping.

Boehm et al. (1996) compared the main features of the two methods, stacking velocity analysis and reflection tomography, by applying them to different synthetic models of increasing complexity and illustrated that for most geological features of practical interest, reflection tomography is the proper tool to use.

Even though one set of data could be used for both inversion and imaging, we chose to acquire two separate lines so as to use unique dataset for each process. Other research has been conducted by using a single set of data (Jaiswal and Zelt, 2008). Jaiswal and Zelt (2008) applied inversion and PSDM to the same seismic dataset from the Naga Thrust and Fold Belt, India, and revealed the presence of a triangle zone that could be promising for exploration. Nevertheless, using two separate set of data avoids the use of modified data for depth imaging and enhances the fidelity of the final depth image.

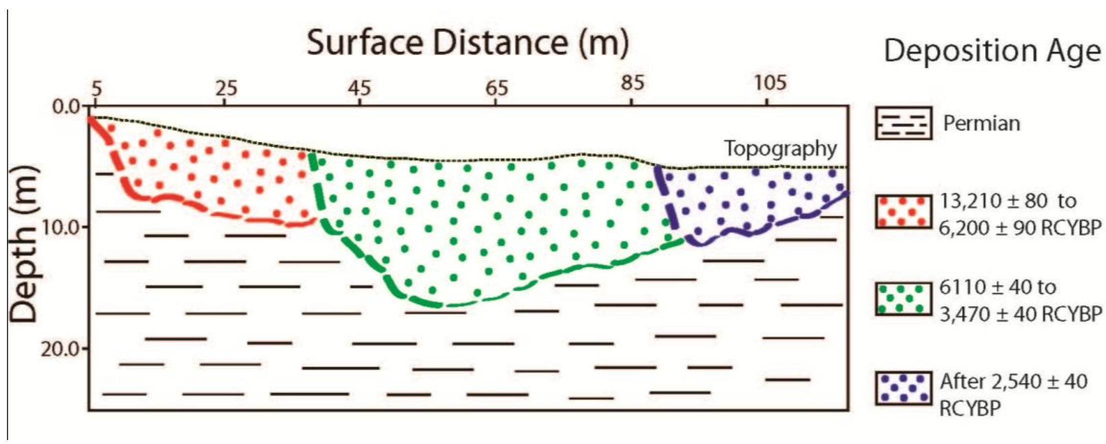

Figure 7: Geologic model with respect age of deposition. (RCYBP: Radio Carbon Year Before the Present).

7. Conclusion

This study suggests that a combination of first-arrival traveltime inversion with pre-stack depth-migration can be a promising approach for interpreting geological structures in an ultra-shallow (<15 m) setting. The key step in this paper is the development of a smooth velocity model by inversion of first-arrival traveltimes which is representative of the large-scale subsurface structures. This model provides a reasonable geological insight and serves as an input for depth migration. The comparison of depth migrated images suggest that velocities from traveltime inversion are better suited for depth-migration than the hand-picked stacking velocities converted to interval velocities; data migrated with the inversion model better images the expected geology. Appropriate datasets for inversion and migration in this paper could only be acquired through two independent acquisitions – first with wider aperture for inversion and the other with denser bin size for migration. This generally might be the case for investigating shallow subsurface with limited resources. Although the presence of cut and fill terraces were generally known in Bull Creek, results from this paper helped better understand the cross-cutting relationship between three relict fluvial floodplains.

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Master of Science/Arts

Thesis: NEAR-SURFACE SEISMIC IMAGING USING FIRST ARRIVAL TIME INVERSION WITH PRE-STACK DEPTH MIGRATION

Major Field: Geology

Biographical:

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Completed the requirements for the Master of Science in geology at Oklahoma State University, Stillwater, Oklahoma in May, 2010.

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Title of Study: NEAR-SURFACE SEISMIC IMAGING USING FIRST ARRIVAL TIME INVERSION WITH PRE-STACK DEPTH IGRATION

Pages in Study: 26   Candidate for the Degree of Master of Science

Major Field: Geology

Scope and Method of Study:

Near-surface seismic reflection imaging: A hybrid acquisition and inversion-migration strategy for near surface imaging.

Findings and Conclusions:

A combination of first-arrival traveltime inversion with pre-stack depth-migration can be a promising approach for interpreting geological structures in an ultra-shallow (<15 m) setting. The key step in this paper is the development of a smooth velocity model by inversion of first-arrival traveltimes which is representative of the large-scale subsurface structures. This model provides a reasonable geological insight and serves as an input for depth migration.

The comparison of depth migrated images suggest that velocities from traveltime inversion are better suited for depth-migration than the hand-picked stacking velocities converted to interval velocities; data migrated with inversion model better images the expected geology. Appropriate datasets for inversion and migration in this paper could only be acquired through two independent acquisitions – first with wider aperture for inversion and the other with denser bin size for migration. This generally might be the case for investigating shallow subsurface with limited resources. Although presence of interglacial drainage system was generally known in Bull Creek, results from this paper helped better understand the cross-cutting relationship between three fluvial paleo-channels.

ADVISER'S APPROVAL: Dr. Priyank Jaiswal