Delineating shallow basement faults on high-resolution seismic reflection data plagued with extreme static in NE Wisconsin, USA

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Summary

Shallow high-resolution seismic reflection techniques proved valuable in detecting, delineating, and advancing interpretations of a regional fault and associate local structural features previously speculated from sparse well data in northeastern Wisconsin. This seismic survey was the first of its kind in this part or Wisconsin and provided solid evidence that the method will work well in this region. Static artifacts on shot gathers were pronounced, and if processed using more routine approaches would have inhibited confident and accurate interpretations of faults along these profiles. CMP stacked sections across these interpolated fault zones uncovered unique and unexpected attributes of the fault feature and associated structures.

Introduction

Accurate images and therefore interpretation of near surface features (anomalies, structures, irregular lithology, etc.) are critical to a wide range of surface and near-surface applications in the fields of engineering, groundwater, geotech, and urban planning, to name a few. Cross sections generated from sparse well data are common working products for many of these applications. Exclusive use of these well-based products represents one of the biggest risks to any surface or near surface improvement or structure. Localized anomalies or changes in geology or hydrology at wavelength shorter than the prevailing well spacing could result in errant designs with potentially catastrophic consequences for people, environment, or property.

Over the last 30 years shallow seismic reflection has been used somewhat sparingly to address a variety of near-surface problems. Economics and complexities associated with difficult settings have hindered routine and widespread use of the method. Commonly, engineers and hydrologists recount less than stellar experiences with shallow reflection when incorporated into past projects, most times these memories are from the distant past. During infancy to early adolescent developmental stages of shallow seismic reflection (1980s and 1990s) there was a general lack of experience amongst near-surface geophysical practitioners. This inexperience with the method many times resulted in overselling and under-delivering. It is no surprise this led to a degree of skepticism that still exists (diminishing a bit) in the user community today. Recent advances in hardware, software, and methods have made the method more cost effective and applicable to a range of problems and settings previously considered out of reach.

One such application is delineating and mapping shallow faults and associated structures where the un lithified portion of the section (overburden) is laterally variable with large vertical velocity gradients. Structural mapping beneath a veneer of glacial outwash, for example, provides challenges in many parts of the world. In these settings the bedrock surface is many times scraped clean of evidence necessary to back out the structural history of the lithified section below. Major faults and associated structures can go undetected or unmapped during standard geologic investigations.

General Geology, Problem, and Approach

A fault zone inferred from sparse drill data represents a modern mystery in Brown County, Wisconsin. Seismic reflection appears to be the best method to map the Precambrian surface in this area, which is expected to be less than 400 m below ground surface with a variable thickness (from less than a meter to as much as 50 m) of Quaternary sediments overlying Silurian dolostone, Ordovician shales and sandstones, with a thick Cambrian sandstone overlying Pre-Cambrian basement (Figure 1). These geologic units, the depth range of interest, and surface conditions are conducive to high-resolution vibroseis reflection profiling. Regionally, with no potential targets for oil and gas prospecting, seismic imaging is very rare throughout this part of Interior Plains and, with the exception of COCORP and university laboratory experiments, none has been documented.

A representative image of the subsurface would be key to unraveling the geologic structures and progression of events that led to the current bed orientations, geometry, and variability in units in this area. Basement is not only grossly undersampled/understudied, it likely holds critical pieces of the tectonic puzzle that cannot be deduced from the overlying Paleozoics. Capturing the relatively small percentage of the Paleozoic section still present, the later portion of the Cenozoic, and the Pre-Cambrian surface will provide geologic information never before seen for this area of Wisconsin.

Considering the complexity of shallow seismic data with highly variable un lithified sections, especially in glacial settings, a large-channel recording system and powerful, yet high frequency and repeatable source was considered essential. A 480-channel distributed seismograph was used to record uncorrelated vibroseis data from triple 28 Hz geophone groupings evenly spaced at 325 per km. A total of around 5 km of
Delineating shallow basement faults on high-resolution data plagued with extreme static full-fold data on two lines were recorded along roads crossing a suspected faulted basement surface (Figure 1).

Borehole data (including electric logs and driller’s logs) from deep water wells in the area provide the only clue as to the geology in this area. With the nonuniform spatial distribution and sparse well placement, a great deal of creativity and speculation is necessary to produce a meaningful and reasonable geologic map. Confidence is only possible with infill data from seismic images.

**Data Acquisition Phase**

Acquisition parameters were refined based walkaway tests at the north end of the seismic line. The recording system included triple Sensor 28 Hz geophones and twenty 24-channel Geodes and one 8-channel DZ seismographs by Geometrics. The seismographs were networked to simultaneously transmit and store the 25MB of data coming from 480 receiver stations and 8 auxiliary feeds in 4 seconds for each sweep. The geophones were planted at 2.5 m intervals in approximate 0.5 m arrays and seated in small divots into firm to hard soil.

An IVI minivib delivered three 10-second, 20-250 Hz upsweeps at each shot location (shot interval was 5 m). Each sweep was recorded individually and stored in an uncorrelated, unstacked format. The telemetried ground force was used for on-site QC only. An independent 8-channel DZ seismograph was mounted in the IVI minivib and dedicated to recording additional baseplate and mass accelerometers used.
Delineating shallow basement faults on high-resolution data plagued with extreme static

for post-acquisition calculation of the ground force. The IVI minivib’s controller computer recorded an independent pair of mass and baseplate accelerometers for drive feedback and in-field QC.

**Data Processing**

Special emphasis was placed on analysis steps and noise suppression prior to CMP stacking. With almost 1250 m of receiver spread active for most shots, significant reduction in fold was necessary to optimize stacked reflection wavelets. Therefore, approximately three-quarters of the recorded traces outside the optimum window were deleted during processing. The nominal fold for reflections from 50 to 200 m below ground surface was around 20 with symmetric azimuthal distributions. This fold reduction proved necessary for maximizing resolution and reducing static effects on CMP stacked sections.

Enhancing the signal-to-noise ratio prior to correlation and vertical stacking was instrumental in the overall quality of these data. Key pre-correlation processing techniques included vibroseis whitening, spectral shaping, coherent noise editing (a variation of diversity stack), and clip wavelet suppression. Post-correlation and pre-vertical stack processing included coherent noise muting, spectral balancing, and high grading gathers (pruning based on quality standards and consistency of wavelets). Amplitude adjusting shot gathers after vertical stacking of the second and third sweep at each station improved interpretability (Figure 2).

Post-vertical stacked data signal-to-noise ratio and resolution were improved with the application of severe inside and first arrival mutes (ensuring shallow, coherent events on CMP stacked sections were reflections), < ½ wavelength surface consistent and residual static corrections based on a 150 ms correlation window, fk filter targeting near-surface guided wave, and migration/migration filtering. Velocity analysis and careful statics applications proved vital.

**Interpretations**

**Shot Gather**

Shot gathers are the gateway to the seismic soul, and in so being they are absolutely critical to both accurate processing and interpretation. They also represent the most defensible means of accessing degree of confidence and fitness of stacked sections for integration into existing conceptual models. With the primary objective of this study to map structures beneath this glacial overburden, shot gathers across the major and target fault structure provide a meaningful measure of confidence in final stacked sections. Vertically stacked and amplitude adjusted shot gathers from four locations across the fault zone possess interpretable reflections with unique reflection characteristics on each (Figure 3). Those characteristics are consistent with their relative location to the primary fault scarp. Much of this trace-to-trace “chatter” (static) is indicative of localized changes in material velocities and the first glimpse at the most daunting obstacle to accurate structural mapping from these seismic data.

**CMP Stacked Sections**

Confident interpretation of reflections on CMP stacked sections, and correlating those reflections to reflectors, is only possible on shallow high-resolution CMP stacked sections if sufficient noise (coherent and random) has been removed or

![Figure 2. Amplitude adjusted shot gather before 20 ms bulk shift to adjust to T₀.](image)

![Figure 3. Amplitude adjusted shot gather before 20 ms bulk shift to adjust to T₀.](image)
Delineating shallow basement faults on high-resolution data plagued with extreme static attenuation for reflections to be the dominant coherent energy on shot gathers. It is also imperative for these shallow structural mapping projects that static (which many times can be more than a wavelength trace-to-trace at these frequencies) be removed so apparent structural variations can be related to changes in reflector elevation and not lateral changes in velocity.

A relatively thin and uniform sequence of reflections is interpretable within the Paleozoic section along this profile (Figure 4). The units between the basement reflection and bedrock are characterized by faulting and associated uplift. The narrow (pencil thin) fault zone inferred from drill data is actually almost a kilometer wide, with the major offset zone around 150 m across. Several secondary faults segmenting in the depth range from about 200 m to 20 m below ground surface are evident across the remainder of the disturbed kilometer.

The Quaternary sediments have a surprisingly uniform nature for being principally glacial in origin (Figure 4). The series of reflections above a nominal two-way time of about 50 ms appear to truncate against the bedrock as it rises to the north between about stations 1640 and 1440.

The Precambrian basement high near station 1400 is the upthrown side of the fault, with the majority of the displacement on this major fault accounted for between station 1420 and 1480 (Figure 7b).

**Conclusions**

State-of-the-art shallow high-resolution seismic reflection techniques proved valuable in detecting, delineating, and advancing interpretations of a regional fault and associated local structural features previously speculated from sparse well data. If these seismic data are an indication of data quality in this area, the high-resolution seismic reflection should be routinely used to provide a critical link to interpreting geology in this region. Major static problems evident on shot gathers were all but eliminated by reducing fold and maintaining full control of the correlation statics processes and optimizing the velocity assignments.

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