High-resolution seismic reflection to image hydrogeologic sequences
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Introduction
High-resolution seismic reflection has been successfully used to delineate preferential pathways within groundwater systems that represent corridors for contaminant movement in a wide variety of challenging hydrologic settings, many in settings where other methods and/or monitor wells have not been enlightening. For more than four decades, seismic reflection has found utility addressing near-surface groundwater problems where lateral variability of confining layers have inhibited even the most sophisticated flow models developed from monitor wells (Shepers, 1975). Optimizing acquisition and processing parameters while limiting interpretations to only what can be validated on shot records and consistent with wave propagation and reflection theory is essential for making meaningful and reliable contributions to a groundwater flow model and associated monitoring and remediation programs (Steeples and Miller, 1990).

Years of application of the method in a wide range of settings and with a diverse set of imaging objectives has resulted in an excellent collection of case studies that provides guidance for current and future applications and developments as well as evaluations of method feasibility. The seismic reflection method has been used to establish lateral continuity in confining units with thick dry sandy overburdens as well as fine-grained unconsolidated and saturated near-surface settings. Mapping bedrock is an important application where percolation rates in the vadose zone are high and bedrock units are impermeable. Seismic reflection is a viable tool for studying sitewide variability in unconsolidated alluvial sediments where complex vertical migration paths can allow contaminants to easily move between local “confining” layers, leaving zones directly beneath a source contaminant free, while deeper layers, seemingly protected by several aquicludes, are rich in contaminant. The complexity of many depositional settings results in rapid vertical changes in material properties and therefore a need for high-resolution imaging that does not require a priori information or assumptions about the sequential nature of the vertical property changes.

Even with seismic reflection’s many positive and sometimes amazing attributes and capabilities, it is imperative that an awareness of the method’s limitations and true potential in real-world settings be maintained. Near-surface seismic methods do not lend themselves to distinguishing different types of liquids within a groundwater system. For example, distinguishing DNAPLs or LNAPLs from within a saturated interval is beyond the resolution of the seismic tool in real-world settings. However, interrogation of the subsurface in search of lithologies or structures that might represent traps for contaminants has proven very effective. In fact, based on the properties of liquids in the subsurface, it is many times possible to infer traps and likely areas of high concentrations based on mapped reflector structures in conjunction with well control.

Figure 1. This filtered shot gather was acquired using an 8-gauge auger gun and 48-channel recording system. The CMP stacked section possesses an obvious termination in the 150 ms confining unit.
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**Interruption in Confining Layers**

**Monterey, California**

Clearing U.S. Military facilities for public use after base closure requires the surface and subsurface be issued a clean bill of health. At the former Fort Ord Army Post near Monterey, California, as much as 100 m of highly permeable dune sands overlay several aquicludes responsible for perchting and confining the groundwater supply (both fresh and brackish) in the area. In these highly permeable sands, any spill or leak at the ground surface can move rapidly through the vadose zone and contact the unconfined aquifer. Security of the fresh water supply in this area is maintained by locally confining impervious layers (aquicludes) that sandwich key aquifers. Assurance of the lateral continuity of these confining layers is essential to ensure the long-term water supply is protected from surface releases at this facility that have been documented since the 1940s.

Shallow seismic reflection has not been particularly effective in near-surface settings such as the one at Fort Ord, where a thick, dry sand tends to attenuate high frequencies quite rapidly. Ground roll is not only the dominant energy, but generally responsible for minimizing the optimum window. Shot gathers from this site possess high frequency reflections with shot-to-shot coherence and consistency such that a high-confidence CMP stacked section could be produced and interpreted with sufficient confidence to provide assurances concerning the continuity of the confining layers (Figure 1).

**Cherry Point Marine Air Station**

An active overhaul facility operated by the U.S. Marine Corps had a history of uncontrolled release of solvents that were routinely used during aircraft maintenance. The thick sequence of coastal plain sediments at this site is characterized by alternating sands and clays that act to isolate the bedrock aquifer and principal water supply for the air base and surrounding community. Contaminant detected in active water wells was the motivation for a basewide hydrologic investigation designed to determine the migration pathway of the contaminant and the source.

High-resolution seismic reflection was used to search for very localized discontinuities in the overlying confining layers that, based on sporadic borings, was interpreted to be continuous across the entire base. Shot gathers possessed the full complement of seismic energy with the high frequency, hyperbolic reflection arrivals pronounced and isolated from source noise (Figure 2). CMP stacked sections possess a substantial sequence of reflections with a dominant frequency around 180 Hz and a relatively narrow bandwidth as evidenced by the “ringy” or cyclic nature of the reflection sequence (Figure 3). A pronounced breach in the overburden confining layers that can be easily correlated to well log data is evident on the stacked section.

**Extending Confining Layers from Borings**

**Aberdeen Proving Grounds**

Military testing at Aberdeen Proving Grounds in Maryland has been active for more than a decade. Uncontrolled release of a wide range of contaminants has occurred at sites all across this facility. With the known lack of regional continuity in the near-surface coastal plain sediments, it was no surprise that correlating lithologies between even relatively closely spaced boring cannot be done with confidence. Shallow seismic reflection provided critical information about the consistency, topography, and thickness of confining clay
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Shot records consistently imaged over 200 ms of high frequency reflection events at time depths as shallow as 50 ms (Figure 4). As expected, a CMP stacked section possessed strong reflection arrivals but clearly lacks the lateral consistency more suited for high confidence interpretations of reflection sections. Deposition of coastal plain sediments is characterized by localized and complex braided patterns. Success of these data was based on identification of areas with apparent breaks in reflector consistency and in need of more detailed investigations provided by drilling.

**Tahoe**

Growth in the Lake Tahoe Basin of California and Nevada sufficiently increased the demand on fresh water to initiate a systematic groundwater exploration program. The objective of these exploration activities was to identify a prolific source of groundwater that would avoid the use of lake water and associated need to construct a new, costly water treatment plant.

The geology of the Tahoe Basin is relatively unique and consists of as much as 500 m of glacial sediments over faulted granitic bedrock. A graben that resulted from basin and range tectonics defines the lake, which has an average water depth of about 350 m. Installation of highly efficient water extraction wells into the glacial deposit is the ultimate objective. These glacial deposits are the result of at least four unique advances and retreats consisting predominantly of silts and sands. Saturated thickness in many areas around the basin could exceed 350 m. Basin sediments possess a range of permeabilities and therefore provide varying degrees of isolation from surface waters and opportunities for optimized well field placements. Seismic reflection mapped the various distinct zones in key areas around the lake, helping to determine favorable test well locations.

Shot gathers from the Tahoe Basin are of excellent quality and clearly demonstrate the potential of the method to map the distinct silt and sand layers (Figure 5). With the sediment load resulting from at least four glacial episodes, it is tempting to interpret the distinct reflection packets (at least four) as representative of the different glacial cycles. CMP stacked sections possess the lateral continuity and character that should permit the correlation of different reflectors from well to well around a localized area of investigation. The method has significant potential for mapping hydrogeologic horizons around the basin.

**Preferential Flow Along Confining Layers**

Fridley

Understanding the various factors that control transport and fate of contaminants is critical to groundwater management and remediation efforts at most industrial facilities. This need was addressed, in part, by shallow seismic reflection at the Naval Industrial Reserve Ordnance Plant in Fridley,
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Minnesota. The plant’s footprint is over 1 square kilometer, it sits directly on 30 to 50 m of Mississippi River sediments, and is less than 1 km from the river. The manufacturing facility has produced and disposed a wide range of liquid industrial byproducts over its almost half century of activity. On-site disposal has ranged from direct, gravity injection into shallow wells to surface release. Considering the meandering and irregular nature of alluvial deposits in this area and the lack of lateral continuity in lithology and water chemistry between monitoring wells, seismic reflection was tested as a possible approach for mapping individual impermeable zones around the site.

At an industrial site with a highly altered near surface (the result of years of construction and destruction) the effectiveness and quality of results from a seismic survey can be highly variable. Testing at several locations around the facility with unequivocal identification and verification of reflection on shot gathers that correlate to mapped lithologies was essential in avoiding inadvertent interpretations of coherent noise as signal. A strong set of reflections is evident from time depths of 35 ms to over 100 ms (Figure 6). The severe velocity gradient at this site makes NMO corrections extremely difficult and necessitates an unorthodox approach to data processing. The drift confining unit reflection at 35 ms was processed separately from the deeper intra-alluvial events. The long offset tail of the 35 ms reflection was actually considered noise on the data set that contained reflections from within the saturated interval.

Highly irregular reflections from within the saturated interval are expected and the CMP stacked section clearly meets those expectations (Figure 7). In this alluvial depositional environment, lenses and layers truncated by cut-and-fill features are prevalent. Unexpected and yet to be fully explained is the offset in the 35 ms reflection. With the supporting information currently available, this offset feature is interpreted to be a terrace structure associated with a recent meander of the Mississippi River. It is likely a cut-and-fill feature from an ancestral meander.

Conclusion
High resolution seismic reflection has proven an effective and accurate tool for mapping multiple confining intervals at sites across a wide range of geologic settings. However, without sufficient attention to detail, noise can be misinterpreted as signal.

Acknowledgements
We greatly appreciate all the students and staff of the Kansas Geological Survey who have been involved with collecting these data. We also appreciate the involvement of Rich Markiewicz, Bureau of Reclamation; Jose Llopis, U.S. Army Corps of Engineers WES; and Carlene Merey, Harding Lawson. Mary Brohammer’s layout and graphics work have dramatically improved the presentation of this study.
EDITED REFERENCES
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REFERENCES