Journal of Applied Geophysics, 31 (1994) 65-72
Elsevier Science B.V., Amsterdam

Applications of shallow high-resolution seismic reflection to various environmental problems

Richard D. Miller and Don W. Steeples
Kansas Geological Survey and Department of Geology, The University of Kansas, Lawrence, KS, USA

(Received February 22, 1993; accepted after revision April 16, 1993)

ABSTRACT

Shallow seismic reflection has been successfully applied to environmental problems in a variety of geologic settings. Increased dynamic range of recording equipment and decreased cost of processing hardware and software have made seismic reflection a cost-effective means of imaging shallow geologic targets. Seismic data possess sufficient resolution in many areas to detect faulting with displacement of less than 3 m and beds as thin as 1 m. We have detected reflections from depths as shallow as 2 m. Subsurface voids associated with abandoned coal mines at depths of less than 20 m can be detected and mapped. Seismic reflection has been successful in mapping disturbed subsurface associated with dissolution mining of salt. A graben detected and traced by seismic reflection was shown to be a preferential pathway for leachate leaking from a chemical storage pond. As shown by these case histories, shallow high-resolution seismic reflection has the potential to significantly enhance the economics and efficiency of preventing and/or solving many environmental problems.

Introduction

Seismic reflection surveys have been successfully used to delineate subsurface features relevant to petroleum exploration for nearly 70 years. The successful use of the technique for shallow applications depends on several key conditions. First and foremost is the existence of acoustic velocity and/or density contrasts in the subsurface. The second relates to the ability of the near-surface to propagate high-frequency seismic signals. Finally, the acquisition parameters and recording equipment must be compatible with the proposed target, resolution requirements, and environmental constraints of the survey. Recent developments associated with the use of the technique to evaluate environmental sites have enhanced the potential of the technique for cost-effective application elsewhere (Steeples and Miller, 1990).

Shallow high-resolution seismic reflection profiles can be useful both in characterizing shallow structures or anomalies and extending features identifiable in outcrop and surface excavation into the upper several hundred meters of the subsurface. The high-resolution seismic reflection method has only recently developed into a practical and effective tool for identifying shallow (<100 m) structures (Hunter et al., 1984; Jongerious and Helbig, 1988; Treadway et al., 1988; Miller et al., 1989, 1990; Miller and Steeples, 1991; Goforth and Hayward, 1992). The shallow seismic reflection technique is inexpensive (relative to drilling) and can increase the horizontal resolution and often decrease the number of drill holes by an order of magnitude. Seismic reflection is an extremely effective technique for detecting faults and interpreting stratigraphic relationships; depth can only be estimated and lithologies only inferred without confirmation drilling, however.

Application of the technique to several

SSDI 0926-9851(93)E0019-6

problems in a variety of geologic settings has been successful over the last several years. Detecting subsurface cavities that are the result of previous mining operations has been successful in coal mining areas where room and pillar techniques were used to remove a coal seam less than 0.6 m thick and 7 m deep. Voids associated with dissolution mining of salt have been directly detected at 50 m of depth. Faults with less than 3 m of displacement have been detected in a 3 m thick coal seam at depths of over 200 m. This paper briefly discusses three case histories involving the effective use of high-resolution seismic reflection for subsurface mapping related to environmental problems.

Seismic reflection technique

Seismic reflection is a geophysical technique involving time-amplitude analysis of an acoustic wave originating at a point, propagating radially out from that point until contact is made with an acoustic interface, where the wave is reflected back to the surface. Acoustic interfaces can be anything from contacts between geologic units to boundaries associated with changes in grain size to the absence of material resulting from either human or natural removal of material. The reflecting of an acoustic wave from any of these interfaces is similar in nature to an echo in the air from a cliff or canyon wall. Once the time series is recorded, it can be analyzed based on comparisons of wave properties and/or arrival patterns at different source-to-detector distances. These analyses can eventually lead to a geologic cross-section with depth approximations based on time-to-depth conversions and interpretations of geologic features based on wavelet properties and arrival patterns.

The common midpoint (CMP) method, also known as the common reflecting point (CRP) or common depth point (CDP) method, was used to generate the time sections displayed in this paper. The CDP method involves a time adjustment of wavelet arrivals (based on source-to-detector offset and velocity) to simulate vertical incidence, followed by the combining of all wavelets with subsurface reflecting points in common. The resulting section simulates, in the time domain, a geologic cross-section. The primary difference is that interpreted layering (as evident by laterally coherent wavelets) is indicative of acoustic impedance contrasts on seismic sections as opposed to geologic cross-sections where layering is indicative of physical changes in material or ages. The total amount of depth represented by a CDP stacked seismic section is based on recording time, focus of survey (i.e., optimizing parameters to be most sensitive to particular targets), average velocity of material, and total amount and type of acoustic energy source.

Case histories

Detecting voids in a 0.6 m coal seam, 7 m deep in southeast Kansas

Gradual earth subsidence commonly forms shallow sinkholes in heavily undermined areas of southeast Kansas. The gradual collapse of near-surface material into voids commonly less than 5 m in diameter in the 7–10 m deep and 0.6–1.0 m thick Weir-Pittsburg coal have generally resulted in sinkholes less than 3 m in diameter and 0.3 m deep. Most of these subsurface voids are remnants of the room and pillar mining method commonly used in this area.

An accelerated rate of subsidence of a previously dormant sinkhole within 20 m of a set of heavily used railroad tracks represented a potential risk to rail traffic. An approximately four-fold increase in the surface area of this sinkhole suggested possible reactivation of subsidence. A shallow seismic reflection survey was conducted to determine the cause and extent of the subsurface affected area, to allow appropriate remediation, and to ensure the structural integrity and safety of the tracks.

The voids were separated from competent

coal on 12-fold CDP stacked data according to frequency, amplitude, coherency, phase, and signal-to-noise ratio (Fig. 1). The first three positive amplitude arrivals between 10 ms and about 22 ms on the stacked section are refractions. Refractions were purposely not muted to avoid disturbing the reflected arrivals that closely trail the refractions. The coal reflection on field files has a unique frequency spectrum and hyperbolic arrival pattern that distinguishes it from refracted, direct, and air-coupled energy. The two-way arrival time of the coal reflection is consistent with the one-way travel time observed in uphole surveys. The difference in the seismic characteristics of voids and intact coal are obvious when the drill-confirmed voids at station 123 and 144 are compared with the drill-confirmed coal at station 135. The coal reflection at station 135 is of higher amplitude, lower frequency, and is more coherent than the reflection energy of the bounding voids.

The sinkhole's migration path toward the railroad tracks did not appear to directly correlate to interpreted voids. The voids interpreted on seismic reflection data did not appear to be large enough to be responsible for the existing 3 m plus of subsidence. These voids would allow for no more than about 0.2 m of surface subsidence. Surface investigation stimulated by these results suggested the migration path of the sinkhole walls correlated very closely with local drainage patterns of surface water. The original formation of the sinkhole was probably from surface collapse of material within and surrounding a vertical shaft. The recent reactivation and resulting expansion of the sinkhole perimeter was concentrated along a topographic low acting as a channel for surface-water runoff. The erosion associated with the water flow had lengthened the sinkhole along the drainage channel. Absence of water in the sinkhole indicated surface water was probably escaping through a reopened vertical

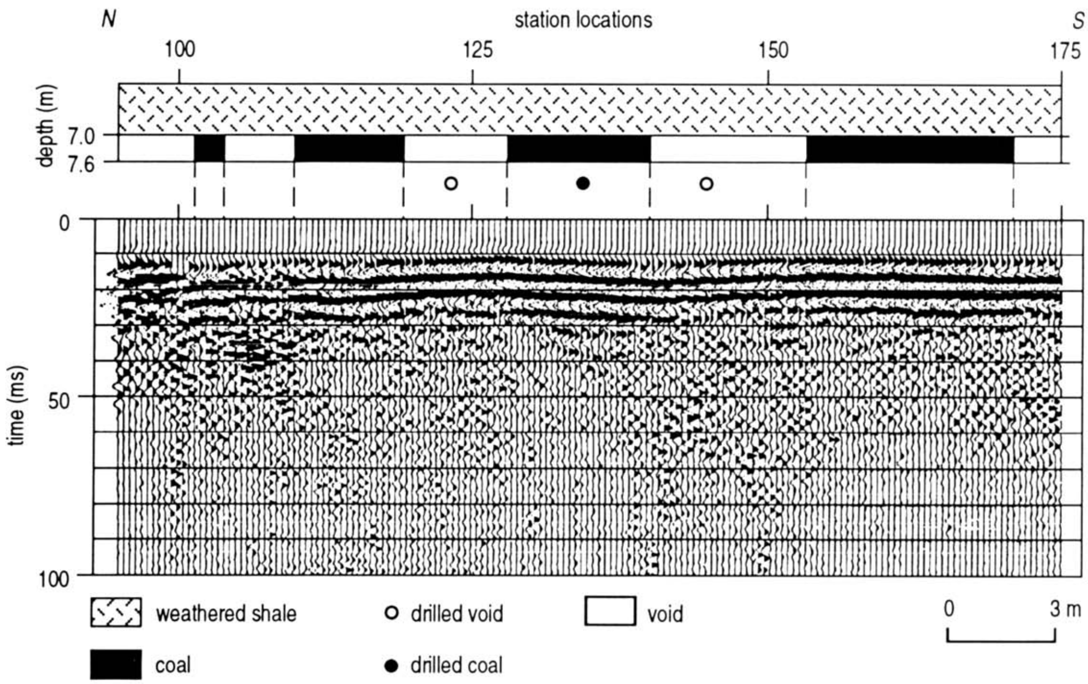

Fig. 1. 12-fold CDP stacked section with generalized geologic cross-section. Drilling, as indicated on the stacked section, confirmed the interpreted voids and competent coal. The first two cycles after the first arrival are refraction.

shaft. The apparent subsidence and growth of the sinkhole was halted by filling the enlarged vertical shaft with grout and rerouting the surface drainage.

Subsidence associated with dissolution mining of salt in central Kansas

The Hutchinson Salt Member of the Wellington Formation, of Permian age, underlies a significant portion of south-central Kansas (Walters, 1977). The thickness of the salt increases from depositional edges on the west and north, an erosional edge on the east, and a facies change on the south to a maximum thickness of over 170 m in central Oklahoma. This increasing thickness from the edges to the center of the salt bed is due not only to increased quantities of salt, but also to more and thicker interbedded anhydrites. Overlying the salt is the Permian Stone Corral anhydrite and approximately 120 m of Permian shale sequences. The salt near the subsidence feature studied here is approximately 120 m deep and 60 m thick.

Surface subsidence within a salt-dissolution well field in central Kansas presented a potential risk to surface structures and transportation facilities. Roof-rock failure and subsidence associated with salt dissolution mining has generally been the result of overmining and can progress either gradually or catastrophically. Determination of the potential extent of continued surface subsidence would allow for more accurate damage estimates and rehabilitation requirements.

The shallow seismic reflection survey was designed to determine the extent of subsurface collapse around a catastrophically developed sinkhole with continued active gradual subsidence. The sinkhole was approximately 15 m in diameter, 3 m deep, and centered approximately on an inactive dissolution well at the time of the seismic reflection survey. Three interconnecting seismic reflection profiles were acquired and processed into 24-fold CDP stacked sections. Orientation of the seismic

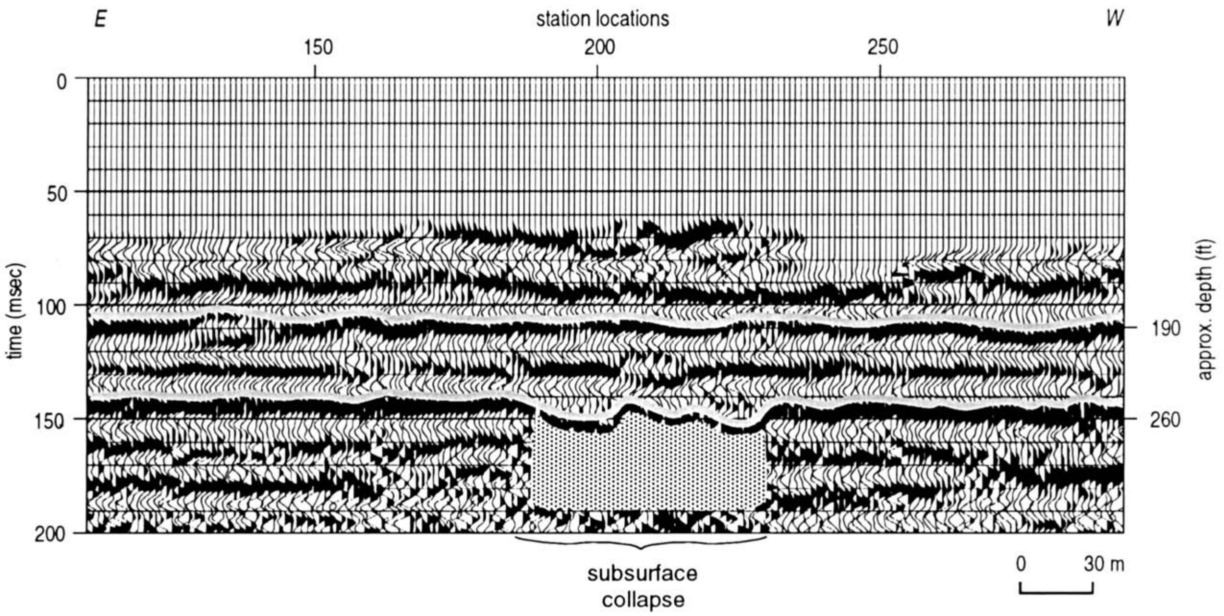

Fig. 2. 24-fold CDP stacked section with void area interpreted (stippling). The lack of coherent reflection energy and the drastic decrease in the signal-to-noise ratio through the stippled area were the criteria used to define the subsurface extent of dissolution.

lines, acquisition parameters and equipment, and processing techniques were designed to maximize the effectiveness of the entire study.

Reflection energy can be identified on raw field files in a time window between about 80 and 190 ms. Reflection irregularities and decreased coherency on the stacked seismic data are suggestive of a subsurface disturbance interpreted to be approximately 50 m in radius and centered on the dissolution well (Fig. 2). The disturbed appearance of the 140 ms reflection, calculated to be from a depth of approximately 80 m, is probably associated with roof collapse into void(s) left as a result of dissolution. The 110 ms reflection appears to be undisturbed by the collapse of units deeper in the section. This suggests roof failure and the associated collapse has not progressed upwards past about 70 m depth. The non-uniform appearance of reflections that probably correlate to collapse features is consistent with seismic interpretations from other dissolution sinkholes in this area (Knapp et al., 1989).

The approximate amount of subsidence and relative size of the interpreted disturbance in the subsurface was consistent for all three lines. General seismic characteristics, line-to-line consistency, and abruptness of interpreted boundaries are probably indicative of a dissolution front. The subsurface disturbed area as interpreted from seismic data was approximately 100 m across with almost 8 m of calculated subsidence of the 140 ms reflector. This interpretation was later verified with a stratigraphic test hole. The eventual surface affected area could be large enough to encompass a paved two-lane road and a railroad spur.

Detecting faults near a leaking chemical storage pond

Detection of isolated fluid seepage from a site approximately 100 m from two potential fluid sources in Hutchinson County, Texas, prompted a study of the near-site geology and hydrology. The geologic study was designed, in part, to determine which fluid source was the origin of the organic fluids detected outside the controlled pond sites. Shallow seismic-reflection techniques were used successfully to image an intra-alluvial layer as shallow as 4 m and as deep as 30 m in the vicinity of the leaking ponds. The major bedrock structure and several associated structural offsets interpreted on seismic-reflection data were confirmed by drilling. An assymmetric graben was interpreted on two of the seismic lines. The overall interpretation combining the seismic data, geologic data, and hydrogeologic data suggests this graben provides increased aquifer storage and controls the lateral movement of alluvial fluids to surface seepage locations. Structure of the bedrock surface and the present hydrogeologic environment are primarily the result of, or are heavily influenced by, dissolution of Permian evaporites overlain by Tertiary sediments (Ogallala Formation) resulting in a graben-like feature between the pond sites.

Seismic sections are shown from two of the eight lines that were shot. The strong reflection is from an interface above the alluvial/bedrock contact. The corehole information allowed correlation of this reflection with a carbonate-cemented bed approximately 5–10 m above the red bed–alluvium contact. Since the primary process responsible for the bedrock structure in this area was subsidence resulting from the dissolution of evaporites, the reflector from the cemented beds served to identify the major alluvial and bedrock structures. The dominant frequency of most raw field data is in excess of 150 Hz. Using a one-fourth wavelength minimum vertical resolution criterion and a normal-moveout velocity of 500 m/s, vertical bed resolution is on the order of 1 m.

CDP line 400 extends from near the corehole-verified bedrock low northward to the bedrock outcrop (Fig. 3). The reflection from the basal Ogallala has good coherency, but is offset in several places as a result of slumping or normal displacement of pre-Ogallala beds. Offsets or bed displacements are present at sta-

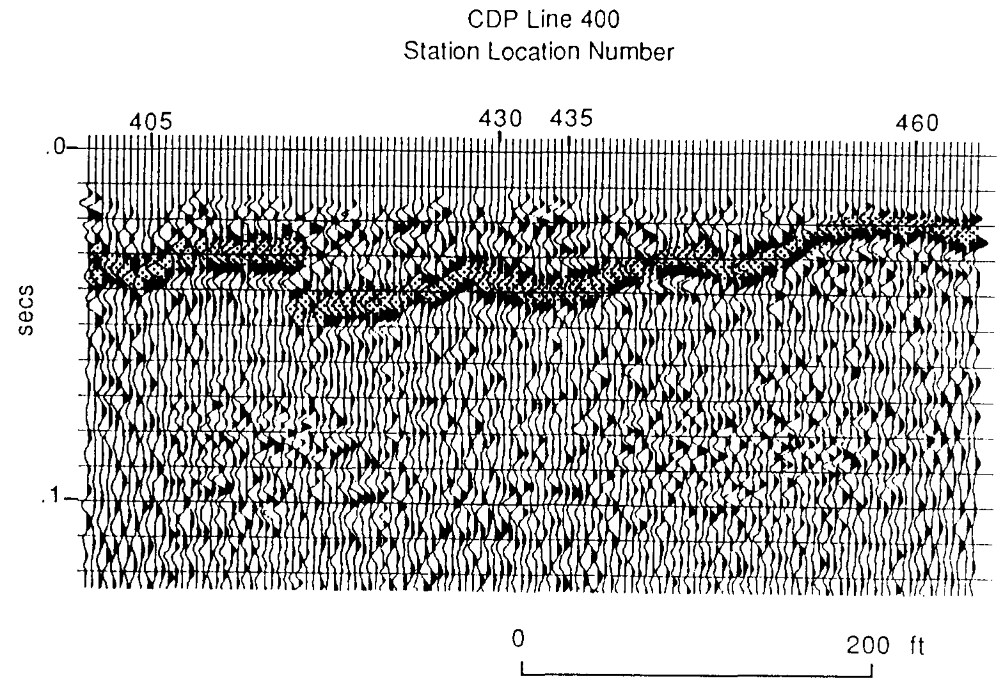

Fig. 3. Basal Ogallala reflector highlighted by stippling. Note faults and apparent general dip toward Station 405 (south).

tions 416, 424, 428, and 439. A narrow graben-like feature with approximately 3 m of down-drop displacement at the south-bounding offset (416) is interpreted between stations 416 and 424. A synclinal structure, probably the result of slow subsidence due to chemical dissolution and slumping, approximately 30 m across and 2 m deep, is interpreted between stations 442 and 468. The primary reflector slopes gradually from about 15 m deep at station 410 to outcrop near the north end of the line.

The asymmetric graben-like feature interpreted on CDP line 700 represents the major secondary structural feature in the area (Fig. 4). The data quality on line 700 is excellent with the basal Ogallala reflector being coherent and having high amplitude. The slump offsets bounding the synclinal graben are at stations 739 and 727. The displacement on the major bed offset at 739 is probably about 10 m, but could be as great as 20 m, depending on the velocity. The slump offset at 727 has experienced only a meter or so of displacement since the deposition of the basal Ogallala. The surface of the basal Ogallala forms a relatively steeply-dipping monocline between stations 715 and 727, with a slope on the order of 7 m vertical to 35 m horizontal (approximately 11°). The shallow, flat reflecting event directly above the graben-like feature was deposited after the subsidence that formed the graben feature. The undisturbed appearance of this shallower reflector would tend to suggest that no subsidence has occurred since its deposition. A hint of deeper reflection energy can be seen between stations 715 and 742 at a two-way traveltime of approximately 90 ms. This reflection energy is probably from the bedrock alluvial interface at a depth of approximately 45 m.

The geologic cross-section derived from a combination of pre-seismic drilling, seismic-reflection data, and post-seismic confirmation drilling resolved most major structural and stratigraphic features of the bedrock and intra-

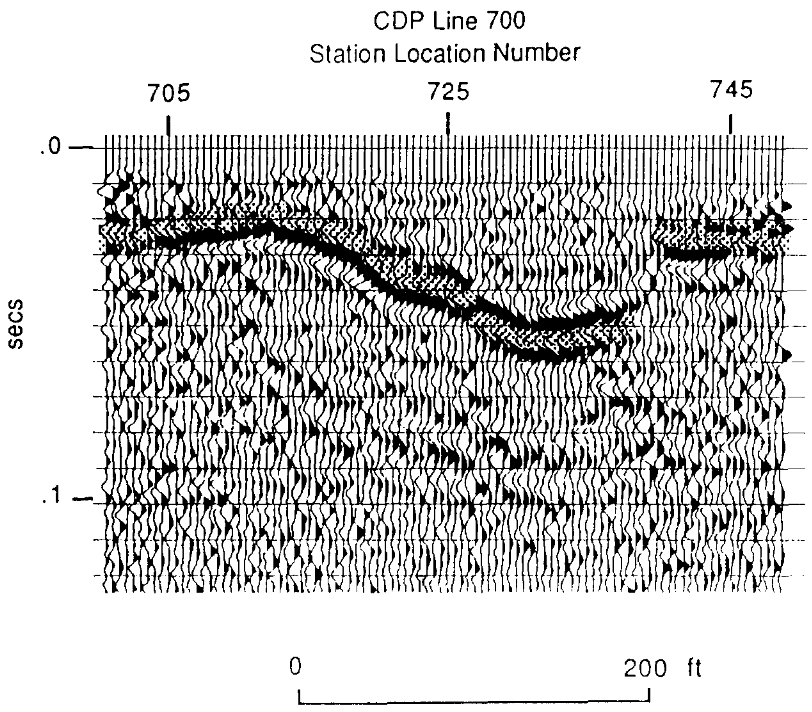

Fig. 4. Basal Ogallala reflector highlighted by stippling. Note the very distinct graben between Stations 727 and 739.

alluvial units. The faults detected on the seismic lines possess sufficient displacement to act as an escape avenue for fluids.

A major bedrock/alluvial collapsed chimney feature located 100 m northeast of closed Pond Site No. 2 in Hutchinson County, Texas, possibly as deep as 80 m, was inferred from seismic data and confirmed by drilling. The primary reflection event on most of the seismic data was from the basal Ogallala at a depth between 4 and 30 m. Multiple bed offsets due to dissolution slumping and other minor structural features were interpreted with the highest concentration of bed offsetting and folding occurring near the center of the collapsed chimney feature. The inconsistent and apparently nonlinear orientation of the local bed offsets, in conjunction with several slump features interpretable on seismic data, are consistent with the suggestion that the bowl-shaped chimney feature is the result of subsidence induced by the dissolution of Permian evaporites.

The prescreening seismic method applied at this site was very successful in providing a preliminary indication of the geologic structure of the area and aided the cost-effective design of a monitor well installation program. This program allowed for the effective siting of new monitor well locations for additionally meaningful data acquisition and reduced the cost related to selecting the number of monitor wells to be installed per dollar spent in acquiring the new subsurface information.

Conclusion

Shallow seismic reflection methods are effective in mapping geologic features of significance in settings as diverse as mineral exploration and void detection. Seismic reflection has been most effective in improving the resolution of existing geologic information in areas where drilling is the only source of data. The seismic method has the potential in many areas to resolve features as small as a meter at a depth of 10 m and faulting with as little as 3 m of displacement at depths in excess of 200 m. With the improvements in electronics, seismic reflection is a cost-effective method of both primary and secondary exploration.

Acknowledgements

We appreciate the support provided by US Office of Surface Mining under Assistance Agreement No. J-5150055, and the North American Salt Co. The authors appreciate the efforts of Larry Schulte and Joel Davenport of North American Salt Co. Manuscript preparation by Mary Brohammer, graphic design by Pat Acker and Jennifer Sims, and editorial comments by Rex Buchanan are greatly appreciated. We appreciate the release of part of this work for publication by Phillips Petroleum Company and Great Plains Geophysical Inc.

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