INTEGRATED USE OF CONTINUOUS SEISMIC-REFLECTION PROFILING AND GROUND-PENETRATING RADAR METHODS AT JOHN'S POND, CAPE COD, MASSACHUSETTS

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ABSTRACT

Continuous seismic-reflection profiling (CSP) and ground-penetrating radar (GPR) surveys were conducted by the U.S. Geological Survey in April 1998 over the northern part of John's Pond, a glacial kettle pond southeast of Otis Air National Guard Base, Cape Cod, Massachusetts. The surveys were conducted to delineate the types and thickness of sedimentary units that may control the infiltration of contaminated groundwater into John's Pond.

Sand-and-gravel deposits, collapse features and recent organic sediments were imaged with the CSP and GPR methods. Hummocky to chaotic reflections were interpreted as sand-and-gravel deposits. Slightly wavy, parallel reflections located in depressions in the sand-and-gravel deposits were interpreted as filled collapse features. Lower amplitude, horizontal, laminar reflections were interpreted as organic sediments. Entrapped methane gas within some of the organic sediments created a reflection zone that obscured deeper reflections in the CSP records.

The CSP and GPR methods provide complementary information over most of the surveyed part of the pond. The methods detect similar interfaces, but a particular interface may produce a stronger reflection in one record than in the other. For example, regions of the pond containing organic sediments with entrapped methane gas, which prevent penetration of the acoustic signal, were penetrated and imaged by GPR. Conversely, regions of the pond containing electrically conductive sediments or deep water, which attenuate the GPR signal, were imaged using CSP. The CSP and GPR data were interpreted to generate a bathymetric map and a map of sediment type and thickness beneath John's Pond.

INTRODUCTION

Recent studies involving land-based drilling have traced a contaminated groundwater plume to the western edge of the John's Pond, but it is unknown where the plume is entering the pond (Air Force Center for Environmental Excellence (AFCEE, 1997a; AFCEE, 1997b). Using continuous seismic-reflection profiling and ground-penetrating radar methods, the U.S. Geological Survey, in cooperation with the Air Force Center for Environmental Excellence imaged the subbottom of the northern part of John's Pond. CSP and GPR were used to identify layers and structures that could control groundwater flow and contaminant transport into John's Pond in order to aid in focusing "on-pond" drilling and environmental sampling (AFCEE, 1997c). This paper presents the results of the geophysical surveys conducted in April 1998.

The pond is located in the Town of Mashapee, southeast of Otis Air National Guard Base (Figure 1). John's Pond is a glacial kettle pond that was formed during the Wisconsinan

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Glaciation and is underlain by a thin veneer of organic material and about 330 ft of glacially deposited sediment overlying bedrock (Masterson and others, 1997).

DATA COLLECTION AND ANALYSIS

Continuous Seismic-Reflection Profiling

CSP systems transmit seismic compressional wave energy (typically from 0.2 – 14 kHz) into the subsurface from a transducer suspended just below the water surface. Seismic wave propagation is affected by contrasts in the acoustic impedance (the product of velocity and density) of the material through which the wave travels. Upon encountering a contrast in the acoustic impedance of the subsurface, a fraction of the energy is reflected and a fraction is transmitted into deeper material. The reflected energy, together with noise, are detected by the transducer and recorded. In Figure 2, a generalized diagram is shown, illustrating the principles of reflection methods. Details on the theory of CSP are discussed in Sylwester, (1983) and Placzek and Haeni, (1995). Some case histories that describe the use of CSP for environmental applications include Wolansky et al. (1983); Morrissey et al. (1985); Haeni (1986); Haeni (1988); Reynolds and Williams (1988); Hughes (1991); Tucci at al. (1991); and Hansen (1993).

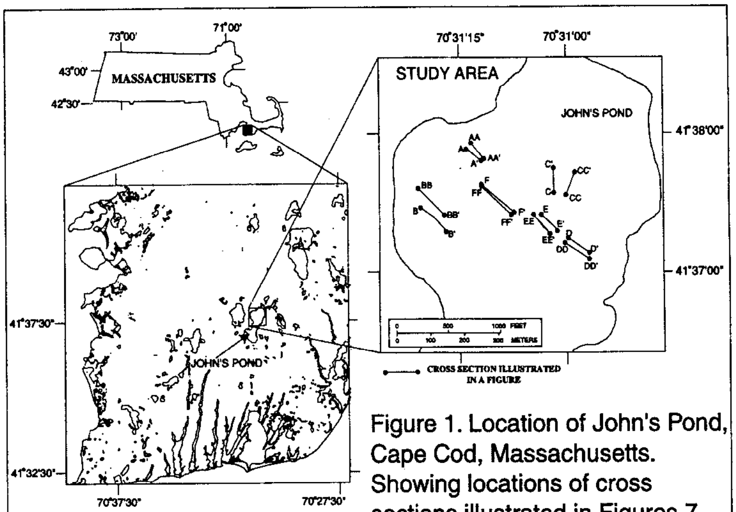

Figure 1. Location of John's Pond, Cape Cod, Massachusetts. Showing locations of cross sections illustrated in Figures 7 to 12

A fixed-frequency CSP system manufactured by ORE International, Inc.[1] was used to collect data on John's Pond. A 7 kHz tuned transducer, was hung from a side-mounted boom and suspended about 2 ft below the water surface. An EPC laboratories, Inc.model 1086 graphic recorder was used to plot data in real-time. During a 1 ½-day period, 5.2 linear miles of CSP data were collected.

Ground-Penetrating Radar

GPR systems transmit electromagnetic waves in the radar frequency range (generally 10-1,000 MHz) into the subsurface from a transmitting antenna on the water surface. Radar wave propagation is affected by contrasts in electromagnetic properties (dielectric permittivity, electrical conductivity and magnetic susceptibility) of subsurface materials (Daniels, 1989). When radar waves encounter contrasts in the electromagnetic properties of the subsurface, some energy is reflected and some is transmitted into deeper materials in a similar manner as CSP. Reflected energy is detected by a receiving antenna and recorded. Detailed discussion of the theory of GPR is discussed in Daniels (1989) and in Beres and Haeni (1991). Some case histories that describe the use of GPR on water bodies include Wright et. al. (1984); Haeni, et. al.

1. All trade names used in this paper are for descriptive purposes only and do not signify an endorsement by the U.S. Geological Survey

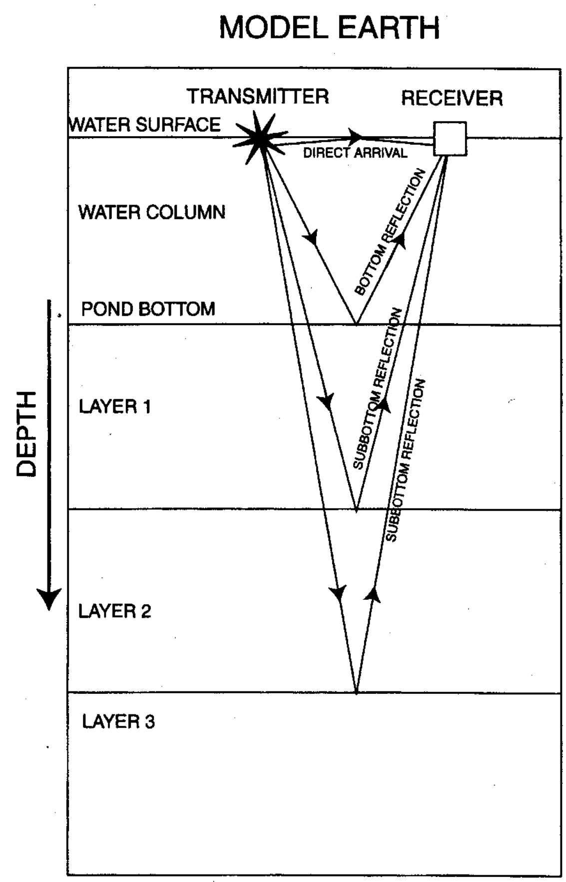

Figure 2. Principles of seismic and radar reflection

(1987); Iivarari and Doolittle (1988); Gorin and Haeni (1989); Haeni and Placzek (1991); Ayotte (1994); Placzek and Haeni (1995) and Haeni (1996).

The GPR surveys utilized a Geophysical Survey Systems, Inc. (GSSI) SIR-10 data-collection system with a pair of modified GSSI 100-MHz antennas to collect data. A graphic recorder was used to plot data in real-time. The radar antennas were floated on the water surface beside a fiberglass-hulled boat in order to prevent ringing and possible interference of the radar signal. During a 1 ½ -day period, 5.9 linear miles of GPR data were collected.

Global-Positioning System (GPS)

A military GPS system was used to determine the boat location. Approximately every minute, a mark was made on the CSP or GPR record at the same time the current location was stored in the GPS. Data were recorded in latitude and longitude format. GPS positioning error is estimated to be less than 12 ft. The boat positioning track lines recorded by the GPS system are shown in Figure 3.

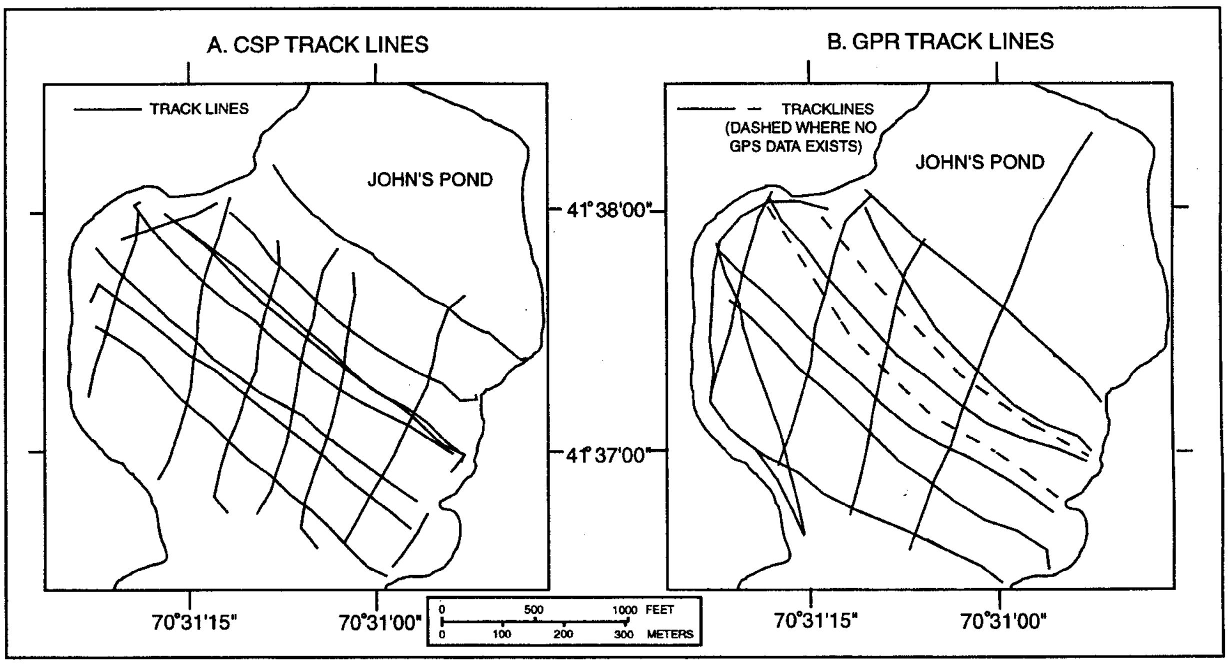

Figure 3. Locations of CSP and GPR track lines collected on John's Pond in April 1998.

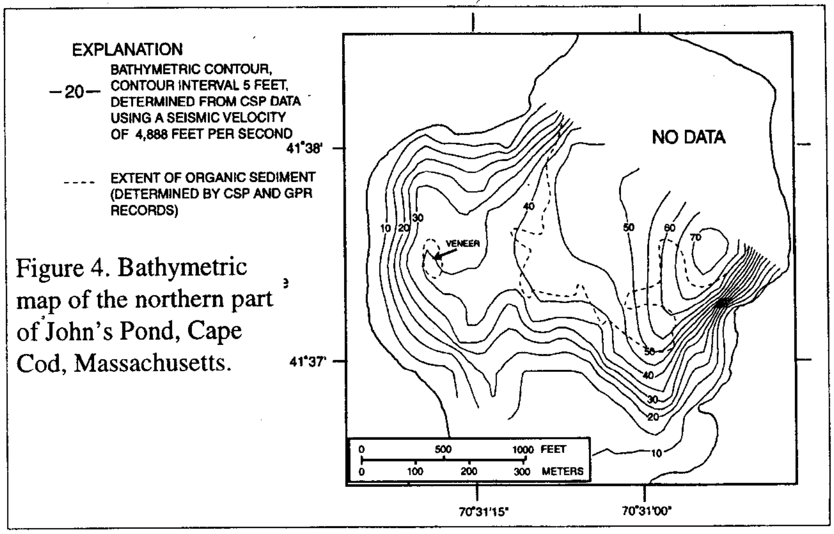

Figure 4. Bathymetric map of the northern part of John's Pond, Cape Cod, Massachusetts.

BATHYMETRIC MAPPING

Depth of water data in the northern part of John's Pond were generated from CSP pond-bottom reflection data using a velocity of sound through freshwater of 4,888 ft/s (Sheriff, 1984). The depth data and corresponding GPS location data were contoured using a kriging interpolation method to produce the bathymetric map shown in Figure 4. Pond depth errors of +/- 5 ft are estimated from sound velocity and vertical transducer positioning error.

The bathymetric map shows that the depth of John's Pond exceeds 70 ft in the northeastern part of the surveyed area. In the eastern part of the surveyed area, the depth of the pond increases rapidly away from the shore with an average slope that exceeds 0.20 ft/ft. In the western part of the surveyed area, the depth of the pond increases less severely, with an average slope of about 0.04 ft/ft.

CHARACTERIZATION OF SEDIMENTS AND STRUCTURES

Based on the reflection characteristics of the CSP and GPR records (Haeni, 1988; Beres and Haeni, 1991), the extent and thickness of different sediments and structures that underlie John's Pond were delineated. Some of the CSP- and GPR-reflection characteristics and their respective interpretations are illustrated in Figure 5. In general, horizontal laminar reflections are associated with fine-grained sands, silt, and organic deposits, whereas hummocky to chaotic reflections are associated with coarse-grained sand and gravel. Interpretation of the CSP and GPR records indicates that the northern part of John's Pond is generally underlain by thick glacial sand-and-gravel deposits that are overlain in places by organic deposits. In general, most of the organic sediments have collected in the deep parts of the pond. Filled collapse features in the glacial sand and gravel deposits were also interpreted.

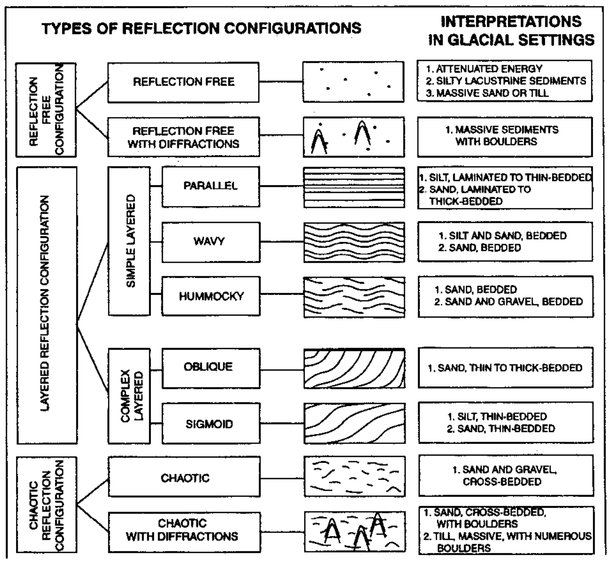

Figure 5. Chart relating typical reflection characteristics observed in CSP and GPR records to lithologic interpretations in glacial sediments (from Haeni, 1988 and Beres and Haeni, 1991)

The CSP, GPR and corresponding GPS positioning data were used to map the extent of the different sediment types and structures. The thickness of the filled collapse structures and

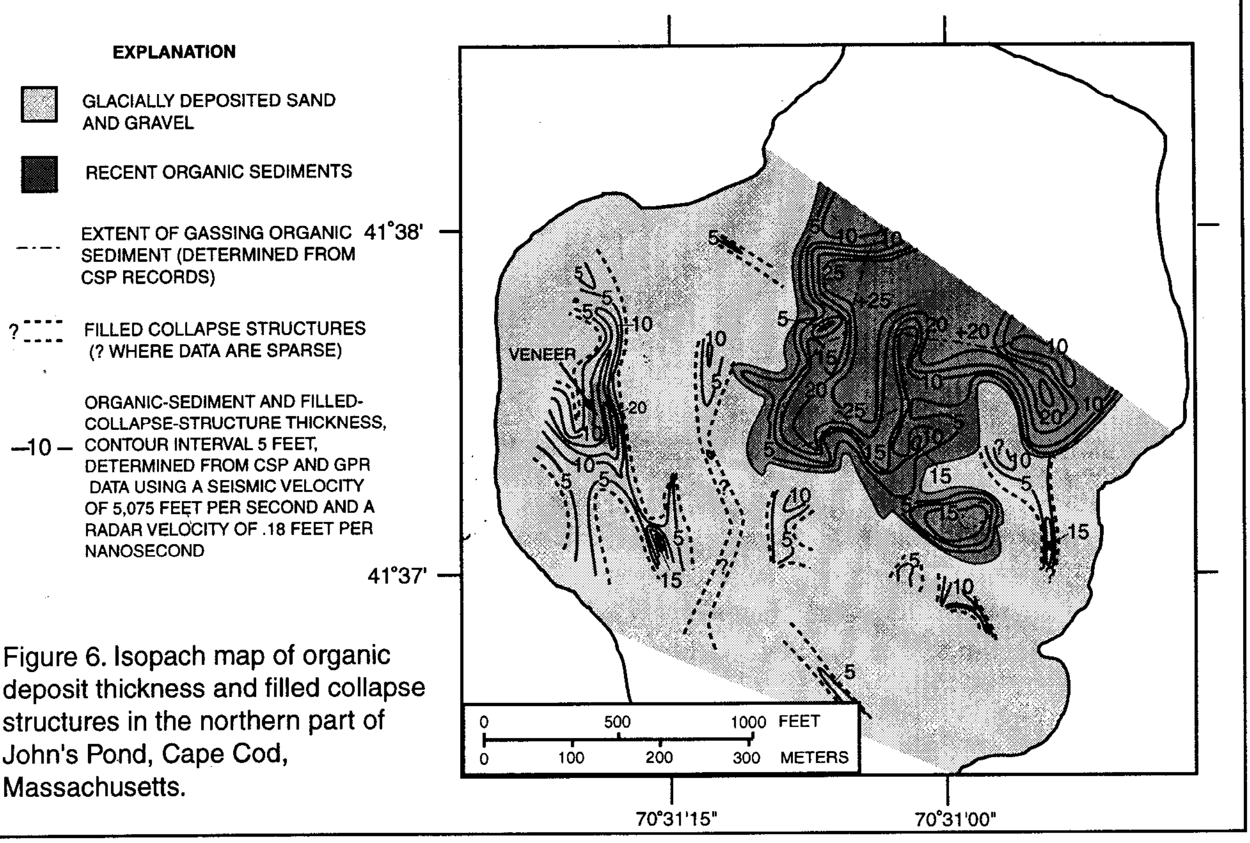

Figure 6. Isopach map of organic deposit thickness and filled collapse structures in the northern part of John's Pond, Cape Cod, Massachusetts.

organic deposits was contoured using the estimated velocity of sound (5075 ft/s; Haeni, 1988) and radar waves (0.180 ft/ns; GSSI, 1987) in saturated sediments (Figure 6). Where data points were sparse, existing data were interpolated.

Sand and Gravel

Glacially deposited sand and gravel underlies the entire pond. Sand-and-gravel deposits are characterized by hummocky to chaotic reflections in both the CSP and GPR records (Haeni,1988; Beres and Haeni, 1991). Discontinuous reflections were observed in the sand and gravel at many locations. The water/sand-and-gravel interface produces high-amplitude reflections in the CSP and GPR records. An example of a reflection in the sand-and-gravel units is shown in Figure 7. The reflections are interpreted either as changes in the mean grain size of the sand and gravel or as a thin layer of finer grained material. In shallow water on the western edge of the pond, GPR detected a reflector at a depth of about 60 ft below the pond bottom. In deeper water (20 to 30 ft), GPR detected reflectors up to a depth of about 30 ft below the water/bottom interface. Reflections from within the sand and gravel were observed in the seismic records to a depth of 15 to 20 ft below the water/bottom interface.

Collapse structures

Several filled collapse structures were interpreted and mapped with the CSP and GPR methods (Figure 6). An example of a filled collapse structure is shown in Figure 8. High-amplitude, slightly wavy, parallel reflections from the fill material are interpreted as stratified sand with some gravel. The collapse structures likely formed during de-glaciation as glacial ice melted, leaving depressions that were later filled with sediment. The thickness of the collapse structure fill ranges from less than 1 ft to more than 20 ft. The collapse structure locations

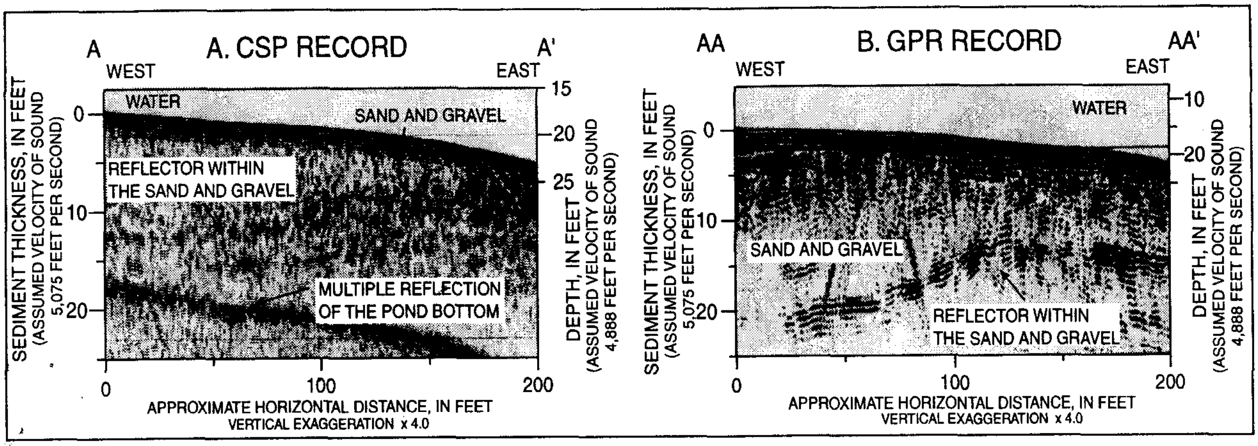

Figure 7. Reflections within the sand and gravel unit imaged by the (A) continuous seismic-reflection profiling method and (B) the ground-penetrating radar method. Data collected on John's Pond, Cape Cod, Massachusetts.

shown in Figure 6 were interpolated between track lines. The collapse structures are small and tortuous; therefore, the true extent and location of the structures is unknown.

Organic Sediments

In the CSP and GPR data, recent organic sediments are characterized by laminar, horizontal, low-amplitude reflections that are draped on the underlying sand and gravel (Figure 9) (Haeni, 1988; Beres and Haeni, 1991). Reflections from the water/organic-sediment interface are of lower amplitude than those of the water/sand-and-gravel interface. The thickness of organic deposits ranges from a thin veneer to more than 25 ft. The seismic signal penetrated more than 15 ft of organic sediments, whereas the radar signal penetrated up to 25 ft of organic sediments, depending on the water depth and the conductivity of the organic sediments. Organic deposits are generally found in the northern part of the surveyed area of John's Pond (Figures 4 and 6). In general, the organic deposits become thicker towards the north and central, deeper part of the pond, although the thickest organic sediment accumulation does not correlate with the deepest part of the pond.

At least two layers of organic sediment are interpreted from reflections within the organic sediments in the CSP and GPR records. In some places, the second layer of organic sediments contains entrapped methane, which indicates the presence of anaerobic methanogenesis

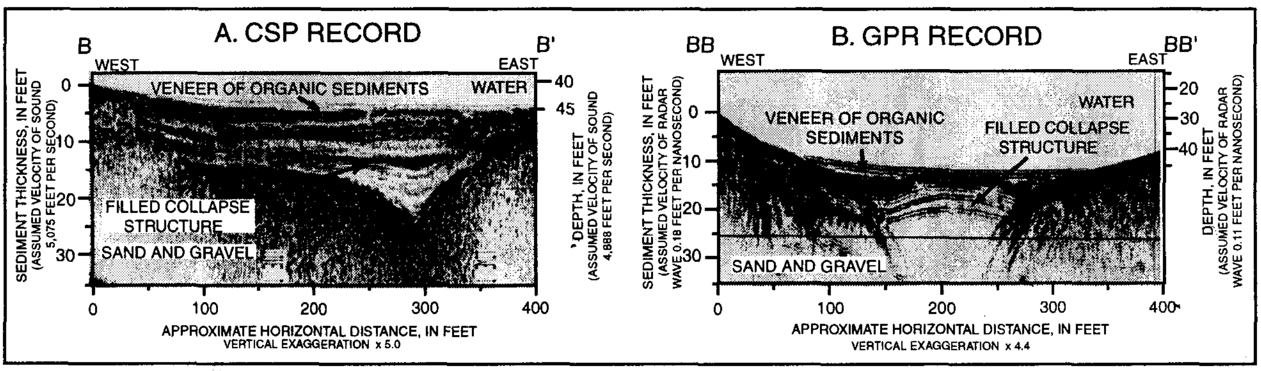

Figure 8. Filled collapse structure imaged by the (A) continuous seismic-reflection profiling method and (B) ground penetrating-radar method. Data collected on John's Pond, Cape Cod, Massachusetts.

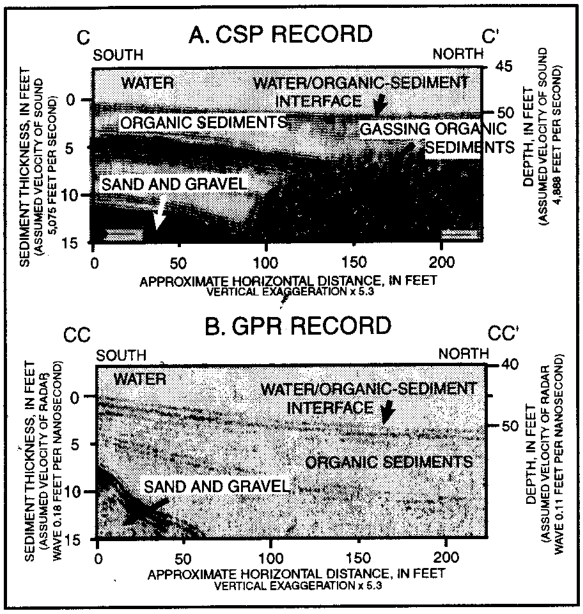

Figure 9. The water/organic sediment interface imaged by the (A) continuous seismic-reflection profiling method and (B) ground-penetrating radar method. Data collected on John's Pond, Cape Cod, Massachusetts.

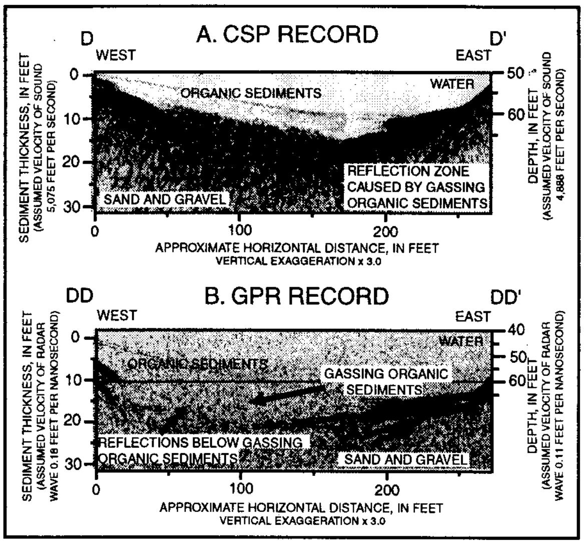

Figure 10. The effect of gas producing sediments on (A) CSP and (B) GPR records. Data collected on John's Pond, Cape Cod, Massachusetts.

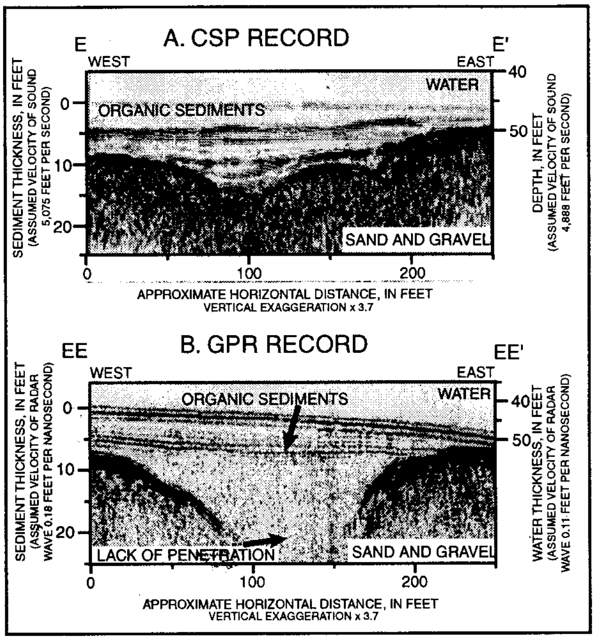

Figure 11. (A) CSP and (B) GPR records. Data collected on John's Pond, Cape Cod, Massachusetts.

(Shubel and Schiemer, 1973). Where it was imaged, the entrapped methane is located about 10 to 15 ft below the surface of the organic deposits.

CSP methods are excellent at detecting the presence of entrapped methane. Methane gas appears as high-amplitude, horizontal reflections with no distinct boundary (Figures 9A, and 10A). Seismic signals are scattered by the gassy deposits, and no stratigraphic information is obtained beneath sediments that contain entrapped methane. GPR cannot be used to detect the presence of gassing horizons, but it can image the materials below those horizons. In Figure 10B, radar data were collected over a location close to where the seismic data shown in Figure 10A were collected, but the entrapped methane did not block the radar signal allowing reflections to be detected below the gassing horizon. However, methane-producing sediments appear to be more electrically conductive and, therefore, more attenuative than non-methane-producing sediments in John's Pond; this reduces radar-signal penetration to less than 6 ft.

INTEGRATED USE OF CSP AND GPR

CSP and GPR methods detect interfaces at similar depths, but a particular interface may produce a stronger reflection with one method than with the other. CSP methods detect changes in acoustic impedance. Acoustic impedance contrasts occur at the water/pond-bottom interface and at changes in sediment type. GPR methods detect contrasts in dielectic permittivity and conductivity, which are usually caused by a contrast in water content that is induced by porosity changes. Interfaces within sand and gravel units were more frequently detected in the GPR records than in the CSP record, whereas the water/organic sediment interface was difficult to delineate with GPR in places but easily identifiable with CSP. Figure 7 illustrates a site where a sloping reflector within the sand and gravel unit is more clearly observed in the radar record than in the seismic record. Figure 9 shows an example of a water/organic-sediment interface more clearly imaged by the CSP method than by the GPR method.

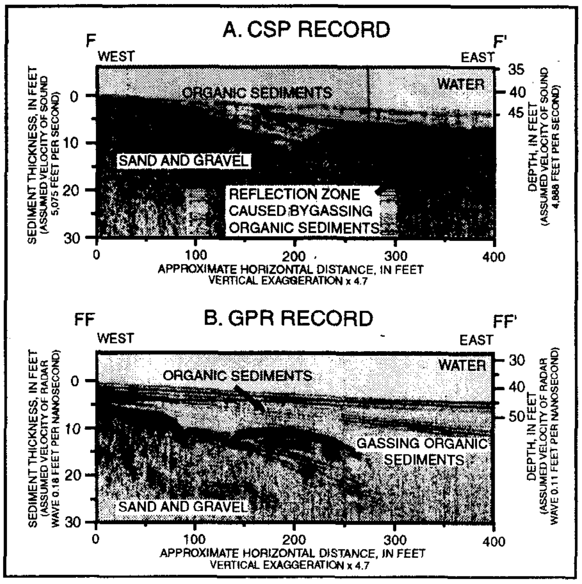

Figure 12. Both the (A) CSP and (B) GPR signals are degraded by site conditions creating coincident data gaps. Data collected on John's Pond, Cape Cod, Massachusetts.

The physical properties of the water, bottom and subbottom in John's Pond often degraded the performance of one profiling method, whereas the other method remained unaffected. In places, the seismic wave is scattered off a myriad of tiny gas bubbles within the methane-producing organic sediments, and the signal strength is quickly attenuated, which creates the reflection zone seen in Figure 10A. The radar signal is unaffected by the gas bubbles and can penetrate through the gassing horizon and image stratigraphic horizons below (Figure 10B).

In the water column, the radar signal is attenuated at a greater rate than the seismic signal, which limits the penetration of the radar wave in deep water. In some areas, the combination of deep water and conductive organic deposits limited the penetration of the radar wave. Under these same conditions, the seismic wave was able to penetrate the material. The organic sediment/sand-and-gravel interface is imaged continuously in the CSP record, whereas the radar signal is attenuated by the water column and organic sediment and does not penetrate deep enough to continuously image the sediment interface (Figure 11).

At John's Pond, the methane-producing organic deposits often appear to be conductive, creating coincident data gaps in the CSP and GPR records. At one location, the seismic signal was scattered by entrapped methane, creating a reflection zone and preventing the return of stratigraphic information from below the gassing horizon (Figure 12A). At the same location, shown in Figure 12B, the GPR signal penetrated more than 20 ft in non-gassing organic sediment and less than 5 ft through methane producing sediment (after traveling through 6 to7 ft of non-gassing organic sediments).

SUMMARY

Continuous seismic-reflection profiling (CSP) and ground-penetrating radar (GPR) surveys were conducted over the northern part of John's Pond on Cape Cod to delineate the extent and thickness of sediments and structures that may control the infiltration of contaminated ground water into the pond. Using a 7-kHz acoustic transducer and 100-MHz radar antennas, 5.2 linear miles of CSP and 5.9 linear miles of GPR data were acquired in April 1998 over the pond.

The CSP and GPR data were interpreted to generate a bathymetric map and a map of sediment type and thickness beneath John's Pond. Sand-and-gravel deposits are characterized by hummocky to chaotic reflections in the CSP and GPR records. Filled collapse structures are characterized by slightly wavy, parallel reflections. Organic sediments are characterized by lower amplitude, horizontal, laminar reflections. In places, entrapped methane scattered the seismic signal creating a reflection zone that obscurred deeper reflections.

The CSP and GPR reflection records provided complementary information over most of the surveyed part of the pond, and each technique supplemented the other in areas of the pond where site conditions degraded the performance of either the CSP or GPR methods. GPR was shown to penetrate entrapped methane within the organic sediments, which quickly attenuated the CSP signal, and was shown to be more useful than CSP at imaging reflectors within sand and gravel units. CSP was shown to have greater penetration ability than GPR in deep water and through non-gassing organic sediments. It was also shown to image the water/organic-sediment interface with greater clarity than the GPR data. In places, the methane-producing organic sediments also were electrically conductive and both signals were quickly attenuated.

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