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Ground penetrating radar: antenna frequencies and maximum probable depths of penetration in Quaternary sediments

Derald G. Smith, Harry M. Jol

Department of Geography, University of Calgary, Calgary, Alta. T2N1N4, Canada

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Abstract

Ground penetrating radar (GPR) experiments were carried out in a gravel pit near Brigham City, Utah, USA, to determine maximum probable depths of penetration for 25, 50, 100 and 200 MHz antennas. We have found that this sedimentary field environment (quartzose-rich, thick, inclined gravel strata) is the most appropriate site known and available for the experimental objectives. With a 1000 V transmitter, 25 MHz antennas are capable of detecting stratigraphy to 52 m and possibly 57 m deep. Excessive signal losses for the 50, 100 and 200 MHz antennas occur at depths below 47, 37 and 28 m, respectively, preventing effective detection of stratigraphic interfaces. From 250 different field experiment sites, we suggest that these profiles represent the maximum probable GPR depths that can be confidently interpreted from any Quaternary unconsolidated sediments. A comparison of results shows a linear trend between different antenna frequencies and the maximum probable depth of penetration, suggesting that the 12.5 MHz antennas can detect strata to 66 m deep. Results obtained using the 25 MHz antennas indicate that at least 52 m of inclined strata, assumed to be foreset facies of gravel, occur beneath the gravel pit floor.

1. Introduction

The maximum probable depth of penetration of ground penetrating radar (GPR) in Quaternary deposits is commonly unknown among GPR users because of the varying physical properties of sediments. We define the maximum probable depth of penetration as the zone beyond which reflected radar signals are too weak (or absent) to be detected by the receiver.

GPR can image "high-resolution" stratigraphy in shallow subsurface sand, gravel, and peat with the best results obtained in clean (free of silt and clay), quartzose-rich, thick, clastic sediments (Jol and Smith, 1991). From our experience, similar sediments saturated with fresh water cause only minor additional signal attenuation. Silt, clay, caliche, and moist saline conditions (coastal marine and some lacustrine sediments) cause severe signal attenuation problems.

During the Late Pleistocene, Lake Bonneville in Utah, USA, occupied the regional Great Salt Lake area and interconnected basins to elevations of 1292 m asl (Gilbert, 1890; Currey et al., 1984). The lake had two prominent levels, which have been termed the Bonneville (upper) and the Provo (lower). These levels and the GPR test site are illustrated in Figs. 1 and 2. During the Provo level, deltas formed at the mouths of many major stream canyons especially along the western slope of the Wasatch Mountains. We studied the Box Elder Creek delta near Brigham City, Utah.

Post-Bonneville stream incisions provided Gilbert (1890) with exposures from which he constructed a model of the internal structure of deltas, a delta type often dominated by inclined strata (foreset beds). Foresets are commonly sandwiched above and below by topset and bottomset beds, respectively. The bedding

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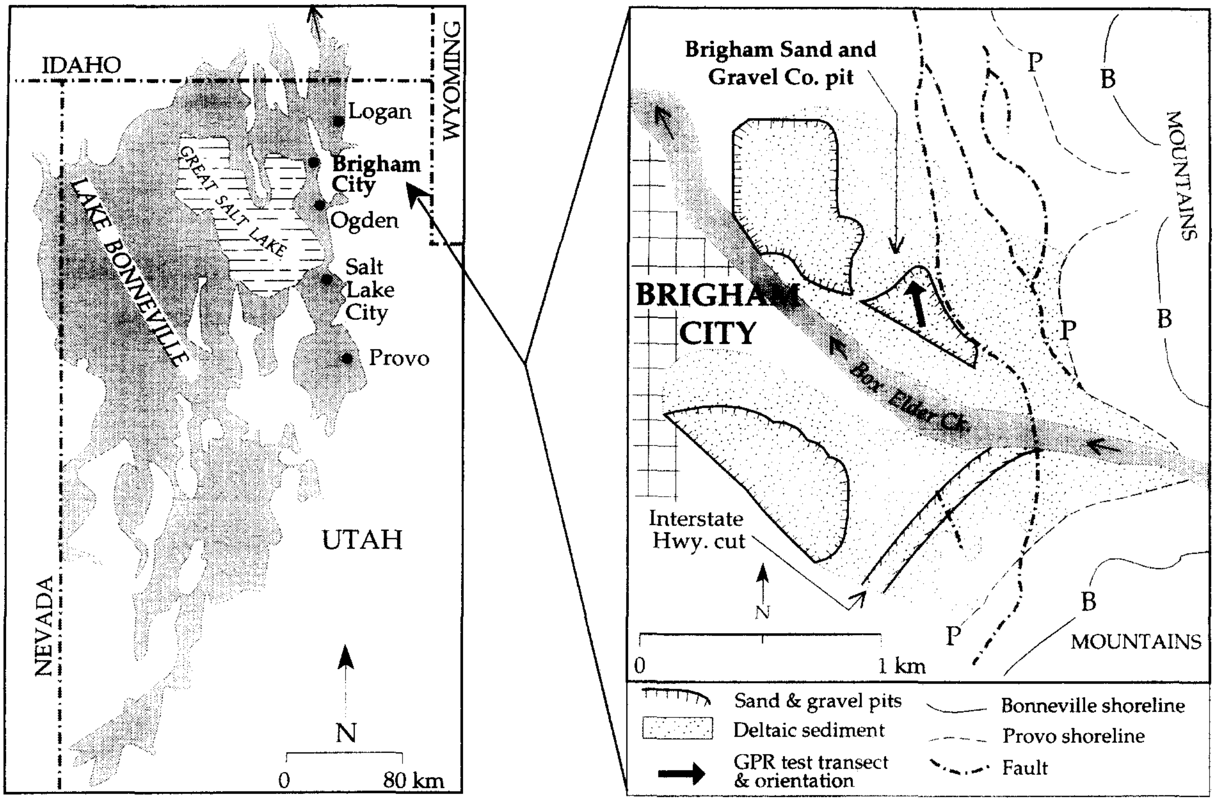


Fig. 1. The Brigham Sand and Gravel Company pit is part of the Late Pleistocene Box Elder Creek delta, Brigham City, Utah, USA (map modified from Personius, 1988; Smith and Jol, 1992a). The dark arrow refers to the location and orientation (345°) of the GPR test transect line.

planes of the inclined strata within the foreset beds provide excellent reflection surfaces for GPR signals. Thus their presence on GPR profiles provides a high measure of confidence that reflected signals are real indicators of buried strata rather than noise, multiples, and/or equipment problems that commonly cause horizontal and wavy reflections.

The Brigham Sand and Gravel Company mines aggregate from a Late Pleistocene delta deposited into former Lake Bonneville (Provo level, 14,500–13,500 yr BP; Currey et al., 1984), and claims to have gravel with the highest quartz content in the Great Salt Lake region (G. Wilkes, pers. commun., 1990; Fig. 1). On the basis of this claim and the exceptional quality of field conditions (Smith and Jol, 1992a), we carried out a series of GPR field experiments on the pit floor to test the maximum depth of penetration at four different antenna frequencies. A nearby borehole indicates that an additional 46 m of gravel occurs below the pit floor (G.A. Wilkes, pers. commun., 1990). From the regional deltaic topography and up to 70 m of steeply inclined gravel strata in the active pit mine-face illustrated in Fig. 3, we anticipate additional deltaic foreset gravel below the pit floor (Smith and Jol, 1992a). Earlier, we observed 32 m of additional inclined strata with impressive resolution in a profile below the pit floor (Smith and Jol, 1992a). The inclined strata (20–25°) in the exposed highwall approximately matches the inclined GPR reflections from the pit floor. These matched inclinations indicate a vertical continuation of the foreset succession visible in Fig. 3.

The use of GPR in sedimentology research is recent and limited, first pioneered by Ulriksen (1982), then advanced by Moorman (1990), Beres and Haeni (1991), Jol and Smith (1991, 1992), Smith and Jol (1992a, b), Baker and Cull (1992), and Jol (1993).

Fig. 2. An aerial view showing the Bonneville and Provo shorelines and morphology of Provo level delta and gravel pits at Brigham City. The upper left pit is the location of the test site. Width of view is 4 km.

Fig. 3. The active mine-face of the Brigham Sand and Gravel Company gravel pit in May, 1993. The pit highwall is 70 m high with inclined, unconsolidated, gravel beds dipping at about 25° toward the northwest.

2. Methodology

Although digital GPR profiles are similar in appearance to seismic profiles, GPR uses an electromagnetic energy source while seismic uses an acoustic source. The theory and methodology of GPR are adequately explained elsewhere (Morey, 1974; Annan and Davis, 1976; Ulriksen, 1982; Davis and Annan, 1989). We used a pulseEKKO™ IV radar system in the reflection survey mode with a 1000 V transmitter. This higher-voltage transmitter was used to provide more energy to the antennas (six times more energy than the standard 400 V transmitter; A.P. Annan, pers. commun., 1991) and improved continuity of reflections. Traces at each step location (vertical trace on profiles) were digitized at a sampling time interval of 800 ps and averaged 64 times. Profiles were processed and plotted using pulseEKKO™ IV (version 3.1) software. An average near-surface velocity of 0.15 m/ns was determined from a common mid-point survey (Annan and Davis, 1976) at 30 m along the transect. An example is shown in Fig. 4.

We determined the optimum transmitter-to-receiver antenna separation from preliminary tests on the pit floor. The separations for the best depth performance for each of the four antennas were found to be: 2 m (25 MHz), 2 m (50 MHz), 2 m (100 MHz), and 0.5 m (200 MHz) shown in Table 1. A GPR station spacing of 1 m was used for all antennas (except for 0.5 m for the 200 MHz) along the same 150 m long transect line.

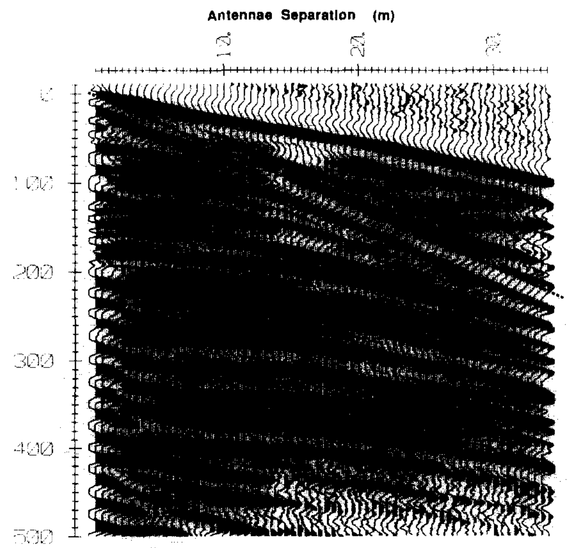


Fig. 4. The common mid-point survey at 30 m along the test transect. The profile was used to calculate the near-surface velocity (0.15 m/ns) from the ground wave (dashed line).

3. Results and discussion

3.1. Maximum probable depth of penetration

Nine 150 m long GPR profiles were carried out along the same line shown in Fig. 5 with the start of the transect (0 m) located 10 m northwest (290°) of the concrete base of the Brigham Sand and Gravel Company gravel crusher and screening plant. From the 0 m starting point the 150 m transect line is oriented at 345°. Nine different combinations of antenna frequency, antenna separation and station spacing were tested and are presented in Table 1. Four of the GPR survey profiles shown in this paper are indicated with bold numbering in Table 1 and are presented, one for each frequency, in Fig. 6A–D.

The profile using the 25 MHz antennas (Fig. 6A), shows the maximum depth of penetration at 690 ns corresponding to a depth of 52 m and possibly at 760 ns corresponding to a depth of 57 m, located at 150 m (ns times are the two-way travel times of the radar signal). At 52 m most reflections appear to begin to flatten; however, one reflection seems to abruptly flatten at this depth to a much lower inclination, continuing to 57 m deep, while other reflections appear to decrease their dip angle. The change in slope angle near the zone of signal loss may represent a change in facies from foreset to bottomset beds. If this is correct, then the change in structural facies may also indicate a change in grain size, perhaps with silt bedding planes sandwiched within sandy bottomsets. The grain size fining and silt would partially account for the loss of signal return. We interpret the prominent continuous reflections as fluvial flood-influenced beds, via coarser grained gravel fed by a river to the delta front then avalanched down foresets and deposited.

The profile using 50 MHz antennas (Fig. 6B) shows the maximum depth of a reflection at 620 ns corresponding to a depth of 47 m located at 139 m. This deepest reflection in the profile is the same as the thick, continuous, prominent reflection shown in the 25 MHz profile. In spite of a significant signal loss at about 35 m, we are confident that the inclined reflections repre-

sent stratigraphy to 47 m deep and not multiples or noise.

The profile using 100 MHz antennas (Fig. 6C) shows the maximum depth of reflections at 490 ns corresponding to a depth of 37 m located at 122 m. Overall, resolution and reflection dip angle has been distorted because the GPR station spacing is not close enough relative to the angle of inclination of the foreset bedding planes. Therefore, the data presented is interpolated from a 1.0 m station spacing to a 0.5 m station spacing.

The profile using 200 MHz antennas (Fig. 6D) shows the maximum depth of penetration at 370 ns corresponding to a depth of 28 m located at 108 m. While considerable signal loss occurs below 22 m, deep faint-to-broken reflections occur at depths down to 28 m. Up to four horizontal reflections below the air wave (uppermost) and ground wave (second) reflections may represent gravel-fill, placed during mining operations. The improved resolution at 200 MHz as compared to the 25 and 50 MHz, indicates other sedimentary structures such as backset beds (Smith and Jol, 1992a) and wavy-like surfaces on the foreset beds.

Table 1
The antenna frequency, associated antenna separation, and GPR station spacing from nine preliminary test surveys (bold numbered data are displayed in Figs. 6 and 7)

Survey No.	Antenna frequency (MHz)	Antenna separation (m)	GPR station spacing (m)
1	25	4	1
2	**25**	2	1
3	**50**	2	1
4	50	1	1
5	100	2	1
6	**100**	1	1
7	200	2	1
8	200	1	1
9	**200**	**0.5**	**0.5**

Backset beds are indicated by the broken "ragged" irregular reflections.

3.2. *Antenna frequency vs. depth of penetration*

A linear relationship exists between antenna frequency (MHz) and maximum depth of penetration (ns

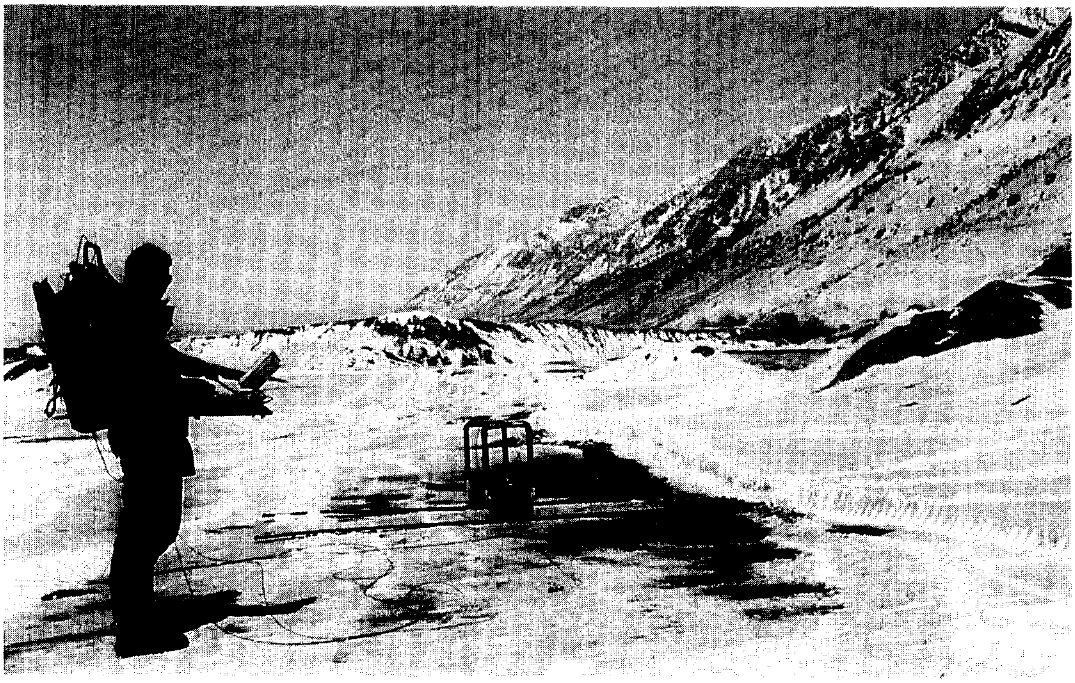
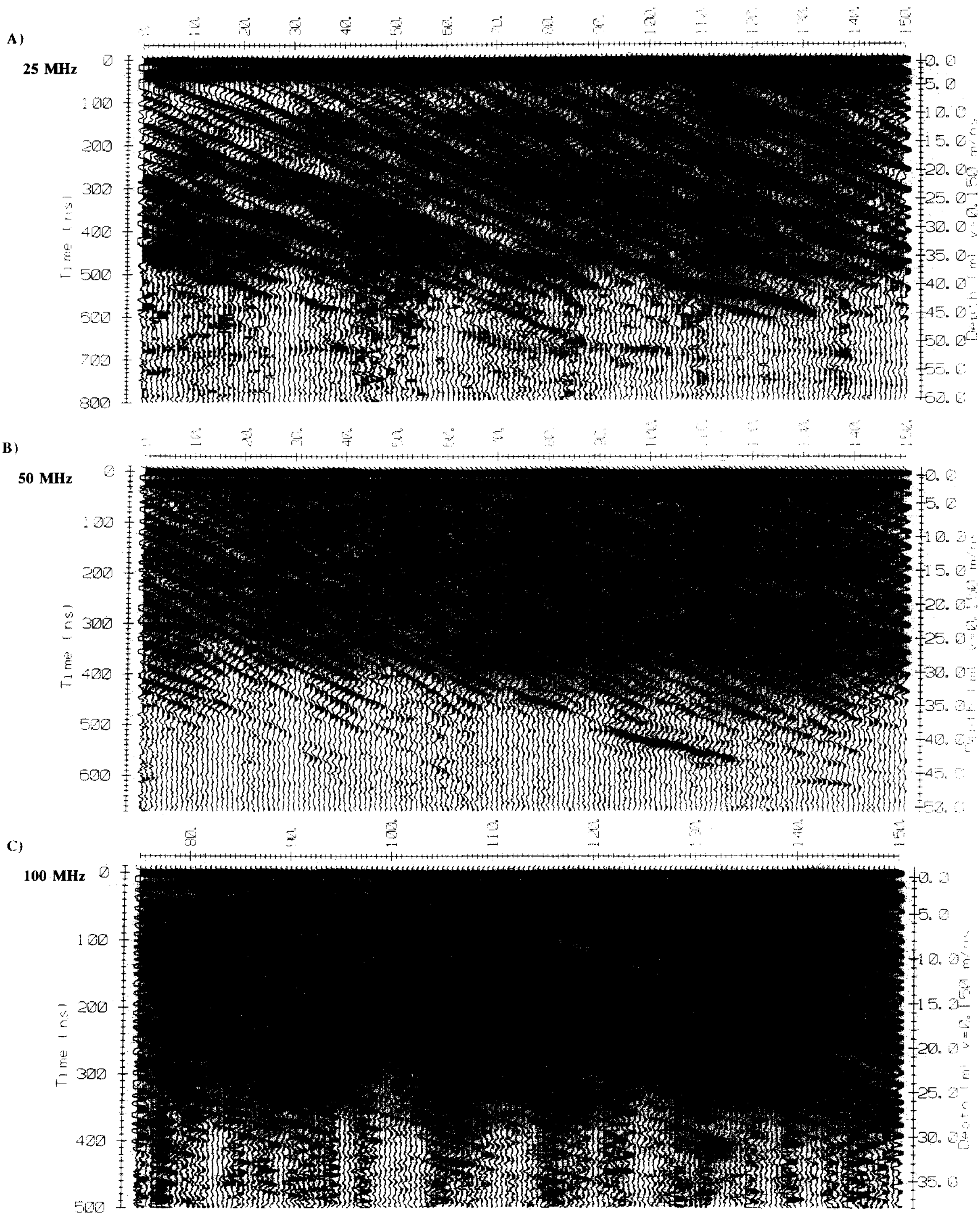


Fig. 5. GPR operation in reflection mode at the beginning of a survey along the test transect. The GPR lap-top computer rests on a platform in front of the operator while the console and power source in the backpack are linked by fiber optic cables to the transmitter and receiver on the 25 MHz antennas (each 4 m long).


A)
25 MHz
B)
50 MHz
C)
100 MHz
Time (ns)

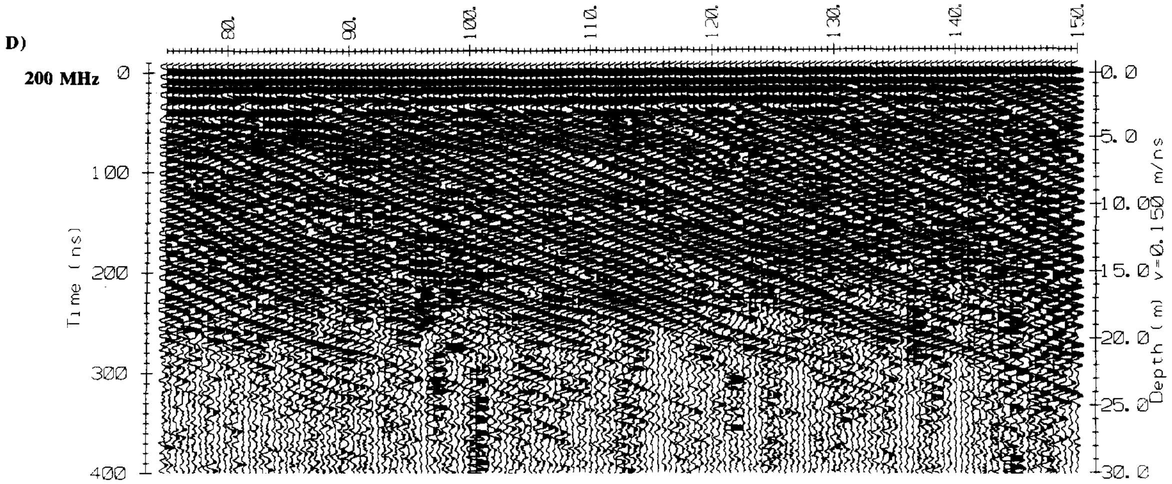


Fig. 6. Four radar profiles from along the test transect shown in Figs. 1 and 5 using different antenna frequencies: (A) 25 MHz antennas (0–150 m); (B) 50 MHz antennas (0–150 m); (C) 100 MHz antennas (75–150); and (D) 200 MHz antennas (75–150). The 25 MHz antenna radar profile along the pit floor shows an additional 45–52 m of inclined strata dipping at 25°, interpreted to be gravel (Smith and Jol, 1992a). From a nearby borehole, 46 m of gravel are reported to lie below the pit floor (G.A. Wilkes, pers. commun., 1991).

and m below the surface) of reflected radar signals depicted in Fig. 7. The depth of the reflection is determined qualitatively from visual interpretation of the deepest series of wiggle traces which show continuity (at least 4 traces). The points are plotted on the basis of the maximum probable depth of penetration from the four different radar frequencies. We believe that these depths are the maximum probable depths that GPR can penetrate in any uniform, unconsolidated, Quaternary clastic sediment. GPR for a given frequency probably cannot detect structure below the best-fit line in Fig. 7. Extrapolation of the linear relationship predicts probable depths of penetration of about 66 m and 18 m, respectively, for 12.5 MHz and 400 MHz antennas in similar sediments.

In earlier comparison tests of different antenna frequencies (50, 100, and 200 MHz), using a 400 V transmitter, 50 MHz antennas were found to be capable of detecting quartzose-rich gravel and sand facies at a depth in excess of 30 m (Jol and Smith, 1991; Jol, 1992; Smith and Jol, 1992a). Deeper penetration may have been possible but the receiver time window was not sufficient in duration. In those experiments, signal losses for the 100 and 200 MHz antennas occurred at depths below 23 and 18 m, respectively, although they provided higher resolution of stratigraphy. These earlier results compare less favorably with the 37 and 28 m maximum probable depths obtained with the same respective antennas using a 1000 V transmitter.

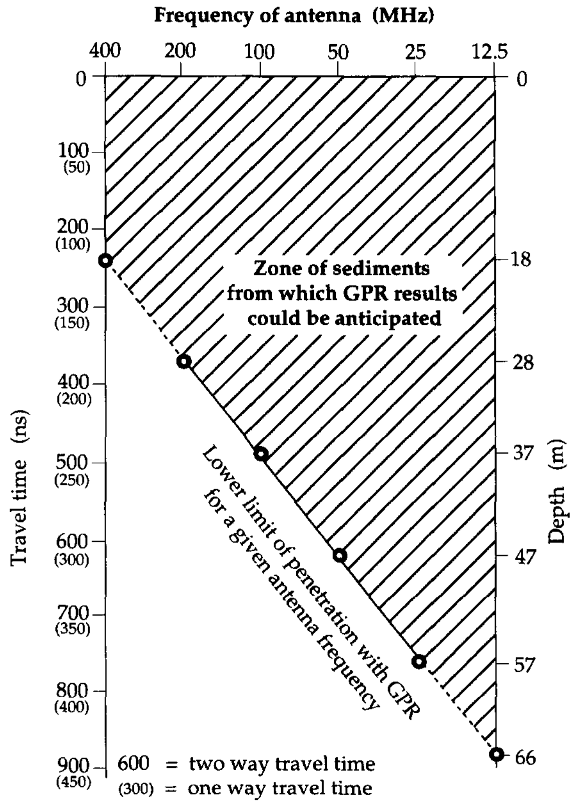


Fig. 7. Linear relationship comparing different antenna frequencies with maximum probable depths of penetration. Interpolation along the best-fit line indicates anticipated maximum depths of penetration for the 12.5 MHz and 400 MHz antennas at 66 and 18 m, respectively.

4. Conclusions

There is a close association between the large-scale sedimentary structures (foreset facies) present in the highwall exposures and in the GPR reflection patterns from below the pit floor at the Brigham City Sand and Gravel Company gravel pit. On the basis of this association, we can predict with a high measure of certainty that the inclined strata and reflections above and below the pit floor are depositionally linked. We suggest that the following maximum probable depths of penetration can be anticipated for the four tested antenna frequencies: 57 m (25 MHz), 47 m (50 MHz), 37 m (100 MHz), and 28 m (200 MHz). Of our 250 other study sites, we believe that the 52 to 57 m depth of penetration using the 25 MHz antennas represents the maximum probable depth of penetration. Our results confirm the claim by G.A. Wilkes (pers. commun., 1990) that these quartzose-rich gravels were both free of silt and clay and extend "150 feet" (46 m) below the pit floor. The quality of the highwall exposure, and the quartzose-rich sediments provide an exceptional experimental site to test the maximum probable depth of GPR penetration.

Given the 70 m of inclined strata exposed in the highwall (Smith and Jol, 1992a), coupled with the additional 45 to 52 m of inclined strata below the pit floor, a sequence of 115 to 122 m of foreset facies occurs in the Provo-level delta at the Brigham Sand and Gravel Company pit. From these results the company has 45 to 57 m more aggregate reserves below the pit floor.

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