Rapid Seismic Reflection Imaging at the Clovis Period Gault Site in Central Texas

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ABSTRACT Using a modified seismic reflection imaging system with rapid translation of receivers, stratigraphic profiles were collected at the Gault site in central Texas. For rapid data collection, spikeless geophone receivers were placed in sand-filled bags at tight spacing, and these receivers were rapidly pulled along the ground surface between shots. Shots were produced by a small hammer strike to a vertical pipe at 20-cm intervals. High quality ultrashallow seismic reflection profiles were collected at a rate of 25 m h⁻¹, significantly faster than what is possible with conventional seismic reflection imaging using individually planted geophones. Ground-penetrating radar was attempted, but abandoned owing to the poor penetration of the radar signals in the clay soils present at the Gault site. Electromagnetic induction grids were collected surrounding each seismic reflection profile, and provided information on near-surface ground water. Seismic reflection images of Gault site stratigraphy provided greater depth penetration than accessible from backhoe trenching and coring, and helped to better outline the site geological context. Seismic images reveal coherent reflections at shallow depths (0–2.5 m), and extensive scattering at deeper levels (2.5–8 m), underlain by reflection-free zones. These data are interpreted as clay and gravel layers overlaying palaeostream channels carved into the limestone bedrock. Where comparative data were available, the geophysical findings were corroborated by observations of site stratigraphy in archaeological excavation units, backhoe trenches and cores. Seismic reflection studies at the Gault site revealed a palaeochannel filled with pre-Clovis age sediments. Pre-Clovis age sediments are not known to occur at other locations within the Gault site. They provide a unique opportunity to test for cultural remains of great antiquity. Copyright © 2007 John Wiley & Sons, Ltd.

Key words: seismic reflection; electromagnetic induction; stratigraphy; Palaeoindian; Clovis

Introduction

Although seismic imaging was developed for deep and large-scale surveys, such as hydrocarbon exploration, it has the potential to be a useful tool for archaeological prospection (Witten et al., 1995; Hildebrand et al., 2002). Recent studies have shown that seismic reflection imaging may be adapted for ultrashallow depths by using broadband seismic sources with good sensor ground coupling (Baker et al., 1999a; Steeples et al., 1999). However, the direct application of standard seismic reflection methods for archaeological prospection provides only limited resolution for features at very shallow depth, and allows only small areas to be surveyed because survey speeds are slow owing to the need for...
continued repositioning of large numbers of seismic receivers. The relatively slow and labour intensive nature of seismic data collection is particularly apparent when compared with other near-surface geophysical methods such as ground-penetrating radar, electromagnetic induction and total-field magnetometry, which can be collected at walking speeds.

We present a technique to seismically image the ultrashallow subsurface at high resolution and at a more rapid rate than is possible with standard seismic techniques. Geophones were attached without spikes to a flexible plastic board which was then placed in the bottom of a sand-filled bag and dragged along the ground surface. This approach is applied to study stratigraphy of the Gault site in central Texas. The seismic data reveal gravel-filled palaeostream channels carved into bedrock, and buried stratigraphic features. These findings were corroborated by...
observations of site stratigraphy in archaeological excavation units, backhoe trenches and cores.

**Geological and archaeological setting**

Clovis represents the first well-documented and widespread culture in North America (Meltzer, 2004). Evidence for Clovis occupation has been found from southern Canada to northern Mexico, with Clovis sites ranging in age from 11,500 to 10,900 14C yr BP (Taylor, 2000). Clovis occupations are characterized by distinctive lanceolate fluted projectile points (Marrow and Marrow, 1999), and tend to occur in riparian settings, especially those associated with small streams and springs and near sources of high-quality lithic materials.

The Gault site is the largest known Clovis occupation site west of the Mississippi River. The 16 ha area was occupied repeatedly by the Clovis, probably because of the available water, high quality chert for tool making and surrounding food resources (Collins and Hester, 1998). The Gault site was subsequently occupied by the Folsom cultural tradition and later groups. Cultural materials are abundant at the Gault site, as well as remains of mammoth and smaller animals.

The Gault site has been known and investigated over the past 80 years to depths of 2 m or more (Collins, 2002). Following initial excavations carried out by J.E. Pearce in 1929, the Gault site has been repeatedly investigated both by controlled excavation and by collectors. While looting and controlled excavation have removed many artefacts from the site, these activities mostly were confined to the midden that dominates the upper layers of the site. The midden contains late Palaeoindian and Archaic period artefacts but overlays the Clovis-age deposits below. Excavations below the midden were performed in 1991 after Clovis-age engraved stones were found in submidden valley alluvium by a collector. In 1998, the site was leased for 3 years to perform more complete excavations by a consortium of institutions.

The Gault site is located in a small stream valley in central Texas (Collins, 2002), an environment providing the potential for deeply buried cultural materials. The site is located in the transition zone between limestone uplands (Edwards Plateau) and the alluvium of the Gulf Coastal Plains. The bedrock in this area is Cretaceous limestone overlain by a series of fluvial and colluvial gravel and clay beds, as well as paleosols that have yielded many cultural items. Several active stream channels are present at the Gault site, and outcrops of high-quality chert occur along the stream valley banks (Figure 1).

**Geophysical methods**

In January 2000, three geophysical techniques for site characterization were tested at the Gault site: ultrashallow seismic reflection imaging, ground-penetrating radar (GPR), and electromagnetic induction (EM). The goal of this work was to better understand the Gault site stratigraphy, and thereby place the Clovis and later cultural materials into their geological context.

**Ultrashallow seismic reflection**

The resolving power for seismic reflection imaging is limited by the bandwidth of the energy source and by the frequency response of the sensors (Widess, 1973). High frequencies (small wavelengths) are needed to resolve closely spaced features. Likewise, horizontal resolution is determined by source and receiver bandwidth and spacing. Attenuation and scattering increase for short wavelengths, placing practical limits on the frequency and therefore the overall imaging resolution.

Seismic waves propagate in three modes: primary waves (P), shear waves (S), and surface or interface waves. Typical P-wave velocities range between 50 and 300 m s\(^{-1}\) for dry unconsolidated soils and sediments (Baker et al., 1999b), and 2000 to 4000 m s\(^{-1}\) for near surface bedrock. Shear wave velocities are typically less than half the velocity of P-waves, and surface wave velocities are somewhat less than those of shear waves. Wavelengths for P-waves theoretically range between 400 m for very low frequencies in bedrock (10 Hz and 4000 m s\(^{-1}\)) to 0.10 m for high frequencies in soil (1000 Hz and 100 m s\(^{-1}\)). Resolution, therefore, ranges between hundreds...
of metres within bedrock layers to tens of centi-
metres within soils.

The geometry for seismic reflection locates
sources and receivers at the ground surface. The
source is typically a hammer strike for near-
surface surveys. Geophones are typically ‘plan-
ted’ into the ground with a bottom-mounted
spike pressed into the soil to provide good
sensor-to-soil coupling (Krohn, 1984). The reflec-
ted energy is received by geophones at multiple
locations along the ground surface, at angles of
0–60° from the vertical, depending upon the
depth of the reflector. The sources and receivers
are translated along the ground surface to cover
areas larger than the geophone line or spread.
Reflected energy data are collected as a function
of time, and converted to depth using knowledge
of the propagation velocity.

Steeplpes and Baker (1998) and others have
shown that downsizing traditional seismic reflec-
tion techniques to the submetre scale can be
successful (Bachrach and Mukerji, 2001; Baker
et al., 1999a; Steeples et al., 1999; Schmeissner
et al., 2001). Geophone spacing and/or source
spacing must be decreased to increase horizontal
resolution. Moderate energy sources are needed
to prevent signal clipping and nearfield non-
linear effects (Baker et al., 1999a). The effort
required to translate the system along the ground
surface, however, makes this approach slow
(Hildebrand et al., 2002). To increase survey
speeds, van der Veen and Green (1998) experi-
mented with a ‘landstreamer’ self-orienting
geophones in heavy casings attached to a rubber
mat to provide weight for coupling as the array
was towed along the ground. A follow up experi-
ment (van der Veen et al., 2001) tested the land
streamer on various surfaces with variable recei-
ver spacing to accommodate a range of depths.

To minimize the time and labour required for
ultrashallow seismic reflection imaging surveys,
we modified a conventional system to allow for
rapid movement of the sensors, source and
recording system (Figure 2). The primary modi-
fication was to remove the planting spikes from
the geophones (Mark Products L-14, with a flat
response above about 14 Hz) and mount them on
a thin flexible plastic board in a bag of wet sand.
This approach simulates burying the geophone
array in a layer of soil and provides a means to
move the sensor array rapidly between shot
firings while maintaining good soil-to-sensor
coupling. Two bags, each containing an array of
12 geophones, were used. Sensors in each bag
were separated by 0.05 m and buried in wet sand,
which had a velocity similar to that of the surface
layer. The bags were arranged to form a single 24
sensor linear array with 0.10 m between the 12th
and 13th phones. The source was a 0.30 m long by
0.025 m diameter pipe held vertically on the
ground and struck by a 0.5 kg hammer (Figure 2).
The pipe was kept independent of the geophones

Figure 2. (a) Schematic of shallow seismic reflection system.
Geophones are split between two bags and are mounted on a
flexible plastic board. The seismic source consists of a hammer
blow to a pipe placed between the bags. Seismograph and
cables are attached to a three wheeled cart. (b) Seismic reflec-
tion system in use at the Gault site. Three people were involved
in the data collection including: control of the seismograph,
use of hammer for source and assistance in geophone
movement.

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to avoid direct coupling. The source was positioned between the two bags, offset 0.05 m from the adjacent geophones. Four shots were stacked and recorded before moving the system 0.20 m along line and repeating. This moderate level of stacking helped to increase the energy content without substantially decreasing the frequency content. The other major modification was mounting the seismograph recorder and cables onto a three-wheeled cart so that it could be easily translated along with the sensor array. The seismograph data acquisition and recording system (Geometrics RX-24) was mounted on a jogger/stroller along with the geophone cables and 12 volt battery.

Several steps of data processing were used to convert the raw field data into a seismic reflection image (SIOSEIS, 2003). Seismic traces with the same reflection point (common depth point) were gathered into record sections and stacked based on their shot and receiver geometry. The distance between reflection points was 2.5 cm (one-half the receiver spacing), and the number of shot-receiver pairs sharing the same reflection point was typically four. The sparse fold of these data is somewhat compensated by the close reflection-point spacing, providing significant gain and increased signal-to-noise in the final section, rather than at the time of the stack. All the traces were filtered for frequencies between 200 and 800 Hz, and normal move-out (NMO) corrected (shifted in time to account for path differences to the same reflection point from different receivers). The data were shifted assuming a velocity of 120 m s\(^{-1}\), the P-wave velocity. The time shift owing to elevation variations along

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Figure 3. Walk-away seismic record section from the Gault site collected at the western end of Line 1. Air-wave (330 m s\(^{-1}\)), interface wave (300 m s\(^{-1}\)), P-wave (120 m s\(^{-1}\)) and surface wave (70 m s\(^{-1}\)) arrivals are indicated.
the ground surface was also accounted for. Muting was applied to the beginning of each trace to eliminate the noise preceding the first arrivals of reflected energy. The traces in each gather were summed (stacked) to enhance reflections while reducing noise. An automatic gain control (AGC) was applied with a time window of 0.015 s. Automatic gain control results in more uniform data by normalizing the amplitudes within each time window according to the average absolute value of the signal within the window. The resulting traces were migrated in the frequency–wavenumber domain to focus energy at reflecting points (Stolt and Benson, 1986). The conversion from the time–distance domain to the frequency–wavenumber domain used a pad of 30 traces to help minimize edge effects. Frequency–wavenumber migration assumed a constant velocity (120 m s$^{-1}$). Stacking and migration velocities were estimated from a walk-away section (Figure 3, filtered as described above), and from individual shot records.

**Ground-penetrating radar**

The GPR data are gathered by transmitting pulses of radar energy (100–1000 MHz) into the ground from a surface antenna, reflecting the energy off buried objects, features, or bedding, and then detecting the reflected waves at the ground surface with a receiving antenna (Conyers and Goodman, 1997). The ability of GPR to image objects and structures is dependent on soil and sediment mineralogy, clay content, ground moisture, depth of burial and surface topography and vegetation. Electrically conductive or highly magnetic materials will quickly dissipate radar energy and prevent transmission to depth. The best conditions for energy propagation are dry sediments and soils, especially those without conductive clay minerals.

The Gault site soil proved to be highly attenuative of GPR signals (400 MHz, GSSI SIR 2000) due to heavy rains and the prominence of conductive clay. Despite significant effort (L. Conyers, personal communication) no usable GPR data could be collected at the Gault site due to lack of signal penetration. This was verified using metal pipes inserted at various depths along an exposed excavation trench.

**Near-surface electromagnetic induction**

Electromagnetic induction (EM) uses low-frequency electromagnetic waves to detect changes in near-surface electrical properties. A transmitting and a receiving coil are separated by a fixed distance, with the coil separation setting the depth of maximum sensitivity. The electromagnetic coupling between the two coils is measured as they are translated along the ground surface. Two properties are derived from the electromagnetic coupling: the electrical conductivity and the magnetic susceptibility, obtained respectively from the out-of-phase and in-phase response. As the coils are moved along the ground surface, changes in the EM signal detect changes in the physical and chemical properties of underlying sediments and soils. Most soil and sediments are poor electrical conductors, and therefore the measurements primarily reveal changes in water saturation, the porosity of the materials, concentration of dissolved electrolytes, the temperature and chemical state of the pore water and the amount and types of clays that are present. Metallic objects also produce strong signatures since they are efficient conductors of electrical energy.

At the Gault site, we measured electrical conductivity using two different instruments. The Geonics EM-31 has maximum detection sensitivity for objects and structures at 1.5 m depth, and a maximum penetration depth of 6 m. The Geonics EM-38 has maximum detection sensitivity at 0.4 m depth and a maximum penetration depth of 1.5 m. Two grids of data were collected with both instruments (Figure 1) with measurements taken automatically at 0.4-s intervals at walking speed along tracks separated by 1 m over each survey grid. The data were corrected for walking speed between 5-m separation fiducial marks and then gridded for display.

**Results**

**Seismic velocities**

To estimate seismic velocities we collected a walk-away record section. From this section, wave velocities were determined based on the range-versus-time slope of coherent events. Shot–receiver offsets were measured from 0.6
to 5.0 m, consisting of 10 shot points at increasing range, with stationary receivers (Figure 3). Four shots were stacked before successively moving the shot point away from the receivers in 0.5 m steps. Several seismic phases were identified (Figure 3). The air wave is caused by the sound wave travelling directly to the receivers through the air; it is the first arrival and has a velocity of $330 \text{ m s}^{-1}$. The interface wave travels along a buried interface between two layers, and has a velocity of about $300 \text{ m s}^{-1}$. The P-wave arrives later, having travelled at about $120 \text{ m s}^{-1}$. Surface waves, also called “ground-roll”, travel slower, with velocities of about $70 \text{ m s}^{-1}$.

**Seismic reflection lines**

Two lines of seismic reflection data were collected at the Gault site (Figure 1). The lines were 78 m (line 1) and 75 m (line 2) long and were each completed in about 3 h of field time. Conditions at the Gault site at the time of the survey were ideal for seismic coupling. Heavy rains combined with the high clay content of the area kept the sensor bags coated with site soils and well coupled without the need for geophone spikes.

A shot gather from Line 1 (shot 320, $X = 14.8 \text{ m}$) is presented in Figure 4. A coherent (continuous in range) event is seen at the top of the gather, beginning near the shot-point. This event is the refracted P-wave (Steeples and Baker, 1998). The refracted P-wave occurs immediately after the shot origin time, and so it appears as a line of energy which tracks changes in elevation along the top of the reflection profile (Figure 5). Another coherent event is seen in the shot gather at less than $0.01 \text{ s}$, resulting from a shallow reflecting layer. A series of diffuse reflecting events are seen at later times in the shot gather. The first of these occurs between 0.015 and 0.035 s. The second is located between 0.038 and 0.049 s. Both are roughly bell-shaped in the shot gather, hyperbolic at the top, becoming flat at the bottom. The reflection profile shows coherent but diffuse reflectors at the location of this shot point (shot 320 in Figure 5).

**Line 1 and Grid 1**

Seismic Line 1 and EM Grid 1 are located in the southwest portion of the Gault site (Figure 1). In this region the Buttermilk Creek is divided into multiple tributary streams. Seismic Line 1 runs through the centre of EM Grid 1 and both extend in the east-west direction. They cross two streams, seen as depressions ($X = 22 \text{ m}$ and $60 \text{ m}$) in the seismic reflection profile, which has been corrected for elevation (Figure 5a).

The seismic reflection profile from Line 1 is presented both with and without interpreted reflective events in Figure 5. Three types of signals are present: coherent layered reflectors, point scattering reflectors, and reflection-free zones. A band of coherent energy appears along the top of the entire section (0–0.5 m depth). The consistent character of this return suggests that it is probably due to direct P-wave refracted energy in the upper soil/sediment, rather than a reflector (Steeples and Baker, 1998). At the west end of Line 1 ($X = 0$ to $12 \text{ m}$) are a series of four diffuse but well-layered reflections extending to a depth of at least 6 m, and which conform to the

![Figure 4. Shot record from seismic Line1 (shot 320, $X = 64 \text{ m}$). The traces were bandpass filtered between 200 and 800 Hz, and an automatic gain control window of 0.015 s applied.](https://example.com/figure4.jpg)
elevation profile. These reflectors slope downward following the topography of the stream channel ($X = 15–35 \text{ m}$). Only the topmost reflector continues across the stream channel, albeit with some distortion. The lower reflections are cut off by an area of scattering or point reflections. Below these scatterers is a reflection-free area (Figure 5b). On either side of the western stream channel ($X = 12–18 \text{ m}$ and $32–50 \text{ m}$), the deepest reflections ($4–6.5 \text{ m}$) do not conform to the topography and are truncated when they contact the upper, conformably layered reflections. The profile elevation and top reflecting layers curve downward into a second channel at the east end of Line 1 ($X = 50–68 \text{ m}$). These layers overlie a series of scatterers and a reflection-free area. From $X = 68 \text{ m}$ to the east end of the line, the data are reflection free; the two upper reflectors terminate at $X = 68 \text{ m}$. Several apparently deep ($2.5–6.5 \text{ m}$) reflections directly beneath the stream channel ($X = 60 \text{ m}$) mimic the upper reflectors, and therefore, probably represent multiple reflections in an upper layer, rather than deep reflectors.

Electrical conductivity measured by the EM-31 for Grid 1 show two high-conductivity swaths trending northeast and corresponding to the two stream channels (east = $30–35 \text{ m}$ and $60–70 \text{ m}$ along the northern edge of the grid) (Figure 6a). Areas of low conductivity are present in the northern half of the grid (east = $50–60 \text{ m}$), as well as at the extreme southeastern corner of the grid. High-conductivity anomalies are also present in the EM-38 data for Grid 1 at the

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Figure 5. (a) Seismic reflection profile for Line 1. Data include 393 shot points over 78 m length. Band-pass filter (200–800 Hz), automatic gain control with 0.015 s window, and migration have been applied. (b) Geological interpretation superimposed on the reflection profile. Reflections are represented by solid lines, while reflection-free areas (bedrock) are brick pattern bounded by a dashed line. Gravel is represented by small circles. Bracket indicates the approximate location of trench BHT-4. The vertical line denotes the centre point of Shot 320, given as a shot record section in Figure 4.
Figure 6. Electromagnetic induction data for Grid 1. Data collected with (a) EM-31 and (b) EM-38. High-conductivity areas represent surface water and low areas the presence of bedrock at or near the surface.
locations of the two stream channels (Figure 6b). However, for the EM-38, these high conductivity zones appear broader and are connected along the southern edge of the grid, creating a horse shoe shape around a low located at 55 m east.

Several backhoe trenches were excavated to delineate the site stratigraphy and provide ground-truth for the geophysical data. Trench BHT-2 (Figure 7) was excavated perpendicular to Line 1, with the south end of BHT-2 meeting the east end of Grid 1 (see Figure 1). The stratigraphy in the trench may be representative of that at the east end of Line 1. Trench BHT-4 (Figure 8) lies to the north between the two streams crossed by Line 1, and may be representative of the stratigraphy further upstream in the middle of Line 1. The Lindsey Pit is one of the more extensive recent excavations at the Gault site and has produced many Clovis artefacts at depths of 0.90–1.3 m. The Lindsey pit is located north of the eastern end of EM Grid 1 at the northern end of BHT-2 (Figure 1).

There are three main components of the trench profile BHT-2 (Figure 7): gravel, clay, and limestone bedrock. The trench was excavated to a maximum depth of just over 1 m. The southern end of the trench is gravel overlying limestone bedrock at a depth of approximately 0.75 m. The ground surface slopes downward to the north, bedrock being found at gradually greater depths below the surface. At the northern end of the trench, the bedrock is also overlain by gravel. Overlying the gravel, and at the centre, resting directly on the bedrock, are a series of clay layers with occasional gravel clasts, as well as cultural materials.

The trench profile of BHT-4 indicates two kinds of stratigraphic units. The northwest end has deposits of coarse gravel with interbedded thin layers of clay that thicken to the south. The southeast end consists of a series of clay beds interbedded with thin layers of gravel. A thin layer of clay above a thin gravel bed occurs at the top of the trench along its full length. Limestone bedrock is only encountered in the deepest part of BHT-4, near the southern end at a depth of 1.75 m.

**Line 2 and Grid 2**

Seismic Line 2 and EM Grid 2 run north–south, just south of the fence line marking the northern extent of the property. Buttermilk Creek runs east–west about 25 m south of the southern end of Grid 2. Seismic Line 2 is located at the centre of Grid 2 and extends the entire length of the grid.

Coherent reflections, scatterers and reflection-free areas are present in the seismic reflection profile for Line 2 (Figure 9). A coherent reflector...
is present at 1–1.5 m depth along the entire length of the profile. At 0–17 m north the coherent reflector overlies a reflection free area at about 2 m depth. North of 17 m the reflection-free area slopes downward creating a channel at 6.5 m depth (X = 25–40 m) and terrace at 5.0 m depth (X = 40–75 m) filled with point-scattering reflectors. Within the channel, some steeply dipping reflectors may be present (X = 27–36 m) at 3.5 to 5 m depth.

Electrical conductivity data from the EM31 for Grid 2 (Figure 10a) shows a high-conductivity
zone in the northwestern corner of the grid in proximity to the barbed-wire fence, suggesting an influence from metal for the data in this region. Anomalously high conductivity also appears between 5 and 15 m north, extending in a narrow band across the grid.

Following the collection of seismic data, a backhoe trench (BHT-13) and geoprobe cores were collected parallel to seismic Line 2 (Figure 1). Trench BHT-13 was excavated along 48 m of the northern end of Line 2 starting at 23 m from the south end. Trench BHT-13 was excavated to a depth of approximately 1.5 m. The stratigraphy of the trench is primarily clay layers overlying medium gravel. The top clay layer thickens to the north where an 8-m-long section of the layer has been disturbed by excavations. At the south end of BHT-13 is a thin (approximately 0.5 m) clay layer at about 1 m depth that produced many cultural items during excavation. The culturally rich layer pinches out midway along BHT-13. A third thick clay layer is present below this and persists along the full length of the trench. The base of the trench contains a layer of medium sized gravel. The trench did not encounter bedrock. A series of eight geoprobe cores were excavated along a northwest to southeast transect, 20–25 m west of BHT-13 (Figure 1). This transect shows three major units (Figure 11): limestone bedrock that plunges to the north, a gravel overlain by clay, and which in turn is eroded and overlain by more gravel and clay.

Discussion

The key geological processes which have formed the Gault site deposits are erosion and weathering of limestone bedrock to produce clays and gravels, and the transport of these materials by streams and during flood events. The southwestern portion of the site is at the head of a small valley and is filled by a colluvial/alluvial fan, and drained by multiple streamlets. In this portion of the site outcrops of limestone are near the surface and also form the valley margins. Coarse-grained deposits of boulders and cobbles, with fewer clays, are expected in this portion of the site. The northeastern portion of the site flattens into a small floodplain along the margins of Buttermilk Creek. More clays, fewer gravels, and a greater depth to bedrock are expected within the floodplain deposits. The configuration of stream channels, floodplain, colluvial/alluvial fan and bedrock limestone create a landscape.
which may have varied over the time of site occupation.

The geophysical and trench data presented here sample the two geomorphological environments described above. Line/Grid 1 is at the head of the valley within the colluvial/alluvial fan and multiple streamlets. Line/Grid 2 is in the lower valley floodplain adjacent to Buttermilk Creek. We discuss below how the geophysical and trench data help outline the geological context of the Gault site occupation and excavations.

**Line 1 and Grid 1**

The colluvial/alluvial fan at the head of the valley is sampled by seismic Line 1, EM Grid 1 and trenches BHT-2 and 4. All these data are consistent with erosion of the limestone bedrock to form coarse boulder/cobble deposits with some interbedded clays, and with high energy downslope transport of these materials. Trench BHT-2, along the valley margins, reveals limestone bedrock at 1–2 m depth with poorly layered clay and gravel deposits (Figure 7). This is consistent with the eastern end of Line 1 (Figure 5, X = 55–78 m) where 1–2 m of layered reflections may represent bedded clays and gravels, overlying 1–2 m of chaotic point scattering reflections representing weathered limestone clasts, above a reflection-free basement of limestone. The process of limestone weathering and soil formation does not appear to create a sharp boundary at the surface of the bedrock, given that there is no strong reflection at this location in the seismic image. Rather, Line 1 has a smooth transition.
from point-scattering reflectors, large clasts of weathered bedrock, to a reflection-free zone within the bedrock (below the dashed line in Figure 5b). A shallow depth (<1 m) to limestone bedrock at the eastern end of Line/Grid 1 is also suggested by the low conductivity in this region for both shallow and deeply penetrating EM data (Figure 6, X = 70–80 m).

In the interior of the valley within the colluvial/alluvial fan, BHT-4 reveals a layered mix of boulder/cobble gravels deposited at high energy and interbedded clays deposited at low energy. Limestone bedrock is encountered at a depth of 1.75 m near the southeast end of BHT-4. This sequence may be comparable to the layered upper section of Line 1 located between the two stream channels (Figure 5b, X = 33–53 m). Likewise, a moderate depth to limestone bedrock near X = 50–60 m within Line/Grid 1 is suggested by the low conductivity for both shallow and deeply penetrating EM data (Figure 6). The point scattering seen in Line 1 at depth (2–5 m) beneath the western stream channel (X = 23 m) suggests boulder/cobble stream gravel deposits.

Seismic data from Line 1 at 3–6 m depth suggest at least one period of erosion and downcutting of the colluvial/alluvial fan deposit and underlying bedrock. Between 32 and 50 m in Line 1 (Figure 5), a series of truncated beds are seen which may be remnants of an earlier sequence of stream channel sediments. These layers outline a broader channel than at present for the western stream in Line/Grid 1. The boundary between the upper sequence (0–3 m depth) and lower sequence (3–6 m depth) of sediments may represent an erosional surface.

**Line 2 and Grid 2**

The lower valley floodplain is sampled by seismic Line 2, EM Grid 2, trench BHT-13 and the geoprobe core transect. The upper seismic reflector (Figure 9) may be due to an older soil horizon. The reflection-free areas (below the dashed line in Figure 9b) may represent limestone bedrock which slopes downward, creating a broad channel between 20 and 40 m. This channel is filled with gravel of various sizes indicated by abundant scatterers. A stream channel bench cut into bedrock is present on the northern side of the section, covered by gravel. Other reflections within the main channel represent complexly bedded channel fill. The presence of a buried stream channel is supported both by data from seismic Line 2, and by the core transect, which intersected the southern edge of the old palaeochannel (Figure 11).

Topographic contours (Figure 1) suggest that the course of Buttermilk Creek or one of its tributaries once ran north of the creek’s current position. The path of this apparent tributary would have run approximately 10 m south of the palaeochannel seen in the reflection data (Figure 9) according to the topographic data. However, a channel and a tank were dug upstream from the survey area in modern times and may have contributed to a change in the current topography of the area. Seismic data suggest that the main channel passed through the survey area between 17 and 40 m north along Line 2. This is shown by the broad channel carved into the bedrock in this area (dashed line, Figure 9b). The depth of the palaeochannel indicates that the creek may have maintained this position for a substantial period of time.

The bedrock palaeochannel is filled with gravel and clay, possibly from colluvial debris. This can be seen on the core transect where the channel is shown to contain gravel deposits overlain by clay (Figure 11). Seismic data reveal complex layering within the channel, also suggestive of mixed gravel and clay deposits. Line 2 is located within Buttermilk Creek’s modern floodplain. Layers of clay are present at the surface in the trench profile of BHT-13 and the core transect, as well as in the seismic reflection profile. Seismic data indicates bedrock at depths of 5 m or more in the area of the palaeochannel (Figure 9). Trench BHT-13 was excavated to a maximum depth of 3 m (at its northern end, see Figure 11) and did not reach bedrock. Nor did the core transect reach bedrock along its northern end within the palaeochannel, although cores were excavated to a maximum depth of 3.5 m. Since BHT-13 revealed the presence of Clovis artefacts at depths of 1–2 m, and not below, we suggest that the palaeochannel, which extends to 5 m depth, appears to be filled with pre-Clovis sediments.

The EM data indicate high conductivity in the northwest corner of the grid, caused by the metal
fence present during data collection. The swath of slightly enhanced conductivity on the southern end of the EM grid may be surface water that also caused anomalous reflections in the seismic data (Figure 9, \(X = 10\) m).

Conclusions

Ultrashallow seismic reflection profiles provided useful stratigraphic data at the Gault site in central Texas. By translating geophones along the ground surface within bags and attaching cables and data logger to a cart, time and personnel were significantly reduced for seismic data collection. This allowed collection of a much denser set of reflection data (closely spaced shots) than would otherwise have been possible. The seismic survey required just three people and was accomplished 50 times faster than a standard near-surface seismic reflection survey. By using a small hammer and pipe as the seismic source, rather than the conventional sledgehammer and striking plate, high-frequency energy was produced. Applying a 200–800 Hz bandpass to the data increased the signal-to-noise and emphasized the reflected phases over the other phases. Coherent reflections and point scatterers were obtained for depths of 0 to 6 m.

Defining palaeostream channels and stratigraphy provides improved understanding of the Gault site geological context. Seismic reflection studies at the Gault site have revealed a palaeochannel filled with pre-Clovis age sediments. The presence of the palaeochannel and pre-Clovis sediments was independently confirmed by the core transect data. Pre-Clovis sediments are not known to occur at other locations within the Gault site. By revealing a buried palaeochannel, seismic reflection data may direct future investigations, and provide a unique opportunity to sample pre-Clovis sediments to test for cultural remains of great antiquity.

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