Ground penetrating radar imaging of cap rock, caliche and carbonate strata

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Abstract

Field experiments show ground penetrating radar (GPR) can be used to image shallow carbonate stratigraphy effectively in a variety of settings. In south Florida, the position and structure of cap rock cover on limestone can be an important control on surface water flow and vegetation, but larger scale outcrops (tens of meters) of cap rock are sparse. GPR mapping through south Florida prairie, cypress swamp and hardwood hammock resolves variations in thickness and structure of cap rock to ~3 m and holds the potential to test theories for cap rock–vegetation relationships. In other settings, carbonate strata are mapped to test models for the formation of local structural anomalies. A test of GPR imaging capabilities on an arid caliche (calcrete) horizon in southeastern Nevada shows depth penetration to ~2 m with resolution of the base of caliche. GPR profiling also succeeds in resolving more deeply buried (~5 m) limestone discontinuity surfaces that record subaerial exposure in south Florida. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Ground penetrating radar (GPR) has been widely used to map shallow stratigraphy in siliciclastic environments (e.g., Davis and Annan, 1989; Smith and Jol, 1992; McGearry et al., 1998; Rea and Knight, 1998; Sauck, 1998). The dominant use of GPR in carbonate environments has been the detection of sinkholes or bedrock cavities filled with air, water or sediment (e.g., Beck and Sayed, 1991; Stewart and Parker, 1992; Barr, 1993; Buursink, 1995; Mallet, 1995). We tested the ability of GPR to map carbonate units that form through the dissolution and recrystallization of calcium carbonate on exposed surfaces, including cap rock, caliche and now-buried discontinuity surfaces.

Karst targets that have been identified through the use of GPR include solution cavities, buried sinkholes and epikarstal features such as bedrock pinnacles. With GPR, voids formed by soil piping to underlying major cavities were detected by their characteristic diffraction patterns (Benson and La Fountain, 1984); cavities of 1–2 m depth extent associated with limestone...
fractures were resolved to a depth of 6 to 8 m (Annan, 1992); and voids were detected in gypsum and salt at various localities in Spain (Casas et al., 1996). Sinkholes have been mapped with GPR in a variety of settings, generally on the basis of reflection patterns from their sediment fill (e.g., Beck and Sayed, 1991; Stewart and Parker, 1992; Barr, 1993; Buursink, 1995; Mellet, 1995). Using GPR Benson and La Fountain (1984) imaged bedrock pinnacles and detached blocks within the sediment overburden.

Larger-scale features (tens to hundreds of meters) of carbonate terrains resolved with GPR include depositional layering, post-depositional truncation surfaces and subaerial exposure surfaces. Liner and Liner (1995) describe a GPR survey over carbonate rocks recently exposed by a roadcut. The outcrop revealed a prominent carbonate mound with overdraped strata. The GPR surveys show the carbonate mound, depositional on-lap of overlying beds on the flanks of the mound, thinning of the carbonate layers over the mound and the truncation of strata as they intersected the GPR acquisition surface.


In this paper we present the results of radar surveys aimed at resolving and mapping exposure-related surfaces, including cap rock and caliche.

2. Methods

GPR data presented here were collected using the Sensors and Software, PulseEKKO 100 system with a 400-V transmitter and 50- or 100-MHz antennas. Traces were recorded with 800-ps sampling intervals and represent either a 64 or 128-fold stack. Antenna separation was 2 m for 50-MHz profiles and 1 m for 100-MHz profiles. We processed the data using Sensors and Software, PulseEKKO version 4.2 software package. Post-processing steps include time-zero adjustments, and on some lines 2 or 3-fold trace-to-trace averaging. Velocities are determined from common midpoint profiling at selected locations on each line. As ground throughout the target depth in most settings was either completely saturated or unsaturated, velocities calculated from direct and reflected arrivals vary little throughout the sections (~10%). A uniform velocity is assumed for the depth axes shown.

3. Results and discussion

3.1. Cap rock (Fakahatchee Strand, south Florida)

In the Fakahatchee Strand State Preserve of southwestern Florida (Fig. 1) surficial marine quartz sands are underlain by an irregular cap rock, or hard limestone crust formed by the recrystallization of dissolved calcium carbonate on exposed rock surfaces. Thickness of sands and soil overlying cap rock in the region of study ranges to 2 m, and the hard cap rock layers may span a zone several meters thick. The depth and continuity of cap rock are of hydrological interest as these properties may strongly influence surface water flow and drainage (Duever et al., 1986). Attempts to map the depth to cap rock or limestone bedrock by direct probing showed depths that varied by 1 m or more over distances of a few meters (Mixon and Schindler, in preparation), making it difficult to discern regional and local trends in cap rock depth. GPR surveys were conducted in March 1997 and June 1998 to determine whether radar methods could be used to better image the position and structure of cap rock.

The cap rock in the Fakahatchee Strand region generally overlies late Miocene–early Pliocene Tamiami Formation limestone. Disso-
olution of bedrock and the development of cap rock is facilitated by tree root and algae and fungi penetration (Duever et al., 1986). Although cap rock is generally denser, with lower porosity and permeability than neighboring limestone, it is often disrupted by jointing. Cap rock elevation appears to be an important control on vegetation, as hardwood hammocks form on rises and cypress strands in depressions. It has been suggested that hardwood hammocks overlie harder rocks (Monroe, 1966) with pervasive dissolution of the limestone underlying cap rock (Craighead, 1974) facilitated by root penetration. These hammocks are in places surrounded by bedrock depression "moats". The cypress trees that colonize areas of lower relief contribute similarly to the disruption of cap rock and dissolution of underlying limestone. Continued lowering of the bedrock by dissolution results in a hydroperiod too long for cypress trees, and cypress growth retreats to the margins of the deeper depressions (Duever et al., 1986).

In the immediate vicinity of the surveys presented here, the cap rock is riddled with solution pipes or vertical cylindrical holes 10–40 cm in diameter and tens of centimeters to several meters deep. Spacing between solution pipes ranges from ~0.5 to 1.5 m (Fig. 2). Such solution pipes are probably responsible for the widely varying depths to cap rock determined by probing. Coring (Weedman et al., 1997) and augering indicate alternating layers of rubbly and well-cemented limestone beneath surficial sands and soils. In this region hardwood hammock elevations are ~0.5 m above and cypress strands 0.5 m below surrounding prairie.
Fig. 1. Arcuate boundaries of limestone outcrop are the borders of solution pipes (diameter $\sim 0.25$ m).

100-MHz GPR surveys across the margin of a hardwood hammock (Fig. 3) and through a cypress swamp (Fig. 4) indicate cap rock that is irregular but fairly continuous over tens of meters. As expected, there is more sediment cover ($\sim 2$ vs. $\sim 1$ m) over cap rock in the cypress swamp than in the hardwood hammock. The dissolution pipe dimensions are generally at or below the Fresnel limit of these surveys ($\sim 0.5$ m) but the small diffractions at and below the top of cap rock reflection ($30$ ns on Fig. 3a and $\sim 80$ ns on Fig. 4) reflection suggest the presence of a few larger pipes and the irregular character of this surface. (The signal has been smoothed in Fig. 3a by averaging pairs of adjacent traces.)

On the margin of the hardwood hammock (Fig. 3a), the top of cap rock and the set of irregular reflectors between 50 and 100 ns becomes shallower eastward. While some returns in this time range may represent complex multiples off the upper cap rock surface, several are clearly primary arrivals. These irregular west-dipping reflectors may represent alternating layers of differing degrees of induration within a "cap rock" package, as seen in corings 2 km south and 6 km north of this site (Weedman et al., 1997). The apparent thinning of the cap rock beneath the hammock margin may reflect dissolution adjacent to roots as suggested by Craighead (1974). This survey suggests that this dissolution is pervasive rather than isolated around the root system of individual trees, and that the edge of the hammock has retreated eastward.

The irregular appearance of the cap rock reflector in the cypress swamp ($\sim 80$ ns on Fig. 4) is probably due to the limestone rubble within the overlying sands and the rubbly nature of the surface itself, as seen in auger samples. The reflection from the upper surface of cap rock is less coherent west of $\sim 43$ m, suggesting a long zone of highly disrupted or downdropped cap rock. In Fig. 4, the 100 ns reflector is interpreted as structure within the limestone while the 125 ns feature appears to be a multiple. A stronger or more precise interpretation would require improved groundtruthing and velocity calibration.

3.2. Caliche (Mormon Mesa, southeastern Nevada)

Situated in the western half of the Virgin River depression in southeastern Nevada, the Mormon Mesa is a triangular flat-topped mesa that rises 225 m above the Virgin River to the east and the Muddy River to the west (Fig. 5). The Mesa is comprised of the Muddy Creek Formation, a fluvial siltstone/sandstone sequence that filled many of the basins formed during the late Miocene, and is capped by a thin layer of caliche (calcrete) that follows the subtle topography of the mesa. Formed as a result of pedogenetic processes involving evaporative
Fig. 3. (a) 100-MHz profile across margin of a hardwood hammock. Location is shown on Fig. 1. Reflectors below top of cap rock shoal gradually from prairie to hammock. Data shown with an AGC gain with 250 maximum possible gain and 1.0 pulse width time window and a 2-fold trace to trace average. Station spacing is 0.5 m. (b) Common midpoint profile centered at 65 m on line in (a). Best-fitting velocity for both direct and reflected arrivals is ~0.06 m/ns. Data shown with gain as in (a).

precipitation of CaCO₃ from rainwater and aeolian carbonate dust (Gardner, 1972), the caliche layer averages about 1.5 m thick across the mesa.

The caliche and Muddy Creek Formation are younger than the 10–13 Ma age of deformation associated with the formation of the Virgin River depression (Bohannon et al., 1993). Yet linear ridges occur on the top of the mesa that are overlapped by the caliche surface (Fig. 5b). The ridges appear to be fault scarps or remnant topography from paleo-stream channels. To determine the structural nature of these ridges we imaged the caliche, overlying sands and the underlying sandstone beds within the Muddy Creek Formation.

A test survey was run near the edge of a cliff, where the structure of the caliche could be discerned from below. At this site caliche 0.2–2 m thick overlies a sandy limestone that grades downward to the Muddy Creek Formation sand. GPR profiles were collected with 100-MHz antennas along the caliche surface under very dry
conditions (Fig. 6). (Although 50-MHz antennas yield slightly better depth penetration, the decrease in spatial resolution makes identification of the base of caliche or Muddy Creek Formation reflectors more difficult). Identifiable arrivals appear up to \( \sim 60 \) ns two way travel time. The relatively high amplitude reflection between 25 and 50 ms shows good agreement with the basal caliche–sandy limestone contact seen in outcrop. For example, the thinning of the caliche beneath the investigator in the middle of Fig. 7 corresponds to the shoaling reflector at 27 m in Fig. 6.

Experiments showed comparable depth penetration (2–3 m) in areas capped by caliche and in caliche gaps near the ridges. Where caliche is present, in general little or no structure in underlying strata is discernible in the GPR surveys. Where caliche is absent, subhorizontal reflectors can be imaged within the Muddy Creek Formation. The limited depth penetration unfortunately renders the GPR data inadequate to resolve the origin of the enigmatic ridges. Nevertheless, these surveys suggest that GPR can be a useful tool for imaging the uppermost few meters of the subsurface in regions overlain by caliche.

![Fig. 4. 100-MHz profile along road through cypress swamp. The reflector at 40 ns is interpreted as base of roadfill, but this contact could not be verified directly as augering was only possible off the road. Gain parameters as in Fig. 3, with no trace to trace averaging. Station spacing is 0.25 m.](image)

![Fig. 5. (a) Location of field experiment in Mormon Mesa, NV. (b) Numbers 1, 2 and 3 show parts of three sets of northeast–southwest striking ridges of unknown origin.](image)
3.3. Discontinuity surfaces (Everglades National Park, south Florida)

South Florida contains eight northwest–southeast trending ridges that have typical lengths of 10–20 km, widths usually 100 m or less, and topographic reliefs generally 0.5–1.5 m (Steinen et al., 1995). The ridges are locally referred to as rock reefs and are especially noticeable in aerial photographs of Everglades National Park. Several processes responsible for the origin of the rock reefs have been suggested but not proven, including mid-Pleistocene faulting, the development of fine fractures inducing preferential cementation, and the preservation of paleo-shorelines or paleo-mud banks. In addition, the enigmatic ridges pond surface water on their north sides and affect spatial distribution.
of plants. Since the narrow ridges are many kilometers in length, it is likely they also inhibit subsurface water flow toward the south, but the effects of the ridges on subsurface water flow have never been evaluated. The models proposed for the origin of the ridges can be tested using GPR images of subsurface structure. Therefore, we ran GPR profiles across Grossman’s Ridge (Figs. 8 and 9), along a transect of bore holes.

The exposed bedrock lithology comprises the bryozoan facies of the Miami Limestone of late Pleistocene age, a marine limestone deposited during a period of higher sea level. Subsurface lithology is composed of alternating sequences of marine and fresh water units separated by discontinuity surfaces (Q1–Q5) that record subaerial exposure (Steinen et al., 1995, Perkins, 1977). The discontinuity surfaces are observed in the core samples as impermeable, dense sequence boundaries above and below the porous Miami Limestone sequences.

The transect of bore holes drilled across the northwest–southeast trending Grossman’s Ridge, reveal no offset in Q surfaces indicative of Quaternary faulting. 100- and 50-MHz GPR profiles directly verify the absence of displacement along the Q4 mid-to-late Pleistocene Unit (180,000 years b.p.), including the Q4 discontinuity surface which is consistently observed at 4 m (165 ns) below the rock surface (Fig. 9). While we cannot distinguish the ridge formation mechanism from these data alone, the uniform depth below surface of the Q4 horizon suggests that the process responsible predates the Q4 exposure.

3.4. Velocities

The velocities at the Fakahatchee Strand and Grossman’s Ridge sites (0.06 and 0.05 m/ns, respectively) are less than those typically expected for limestone (~0.12 m/ns (Annan, 1992)). However, our values are substantiated

![Fig. 8. Location of Grossman’s Ridge which lies within Everglades National Park, Florida.](image-url)
Fig. 9. 50-MHz profile across Grossman’s Ridge. Location shown in Fig. 8. Data displayed with AGC with 250 × maximum possible gain, no trace averaging. Traces are corrected for topography. Common midpoint profiles and a core at the 30 m position (shown as location 2 on Fig. 8) verify the velocity and identification of the Q4 discontinuity.

by both common midpoint surveying at each site (for example, Fig. 3b) and by the good agreement between cores or augers and inferred depths to reflecting interfaces. The anomalously low velocities may be due to the high porosity of the limestone (even the highly cemented cap rock has voids and fractures) and the complete ground saturation.

4. Conclusions

Field experiments in south Florida and in southeastern Nevada demonstrate that GPR is an effective tool for imaging carbonate strata that form under subaerial conditions, such as cap rock, caliche and discontinuity surfaces. In the examples shown above, profiles with 50- and 100-MHz antennas resolve strata to 2–5 m depth. In the Fakahatchee Strand, GPR reveals that the cap rock thins in a continuous fashion toward and beneath the margin of a hardwood hammock and changes in the cap rock reflectors through a cypress swamp are inferred to represent varying amounts of rubble at the cap rock surface. GPR mapping of caliche in Mormon Mesa and the Q4 discontinuity in Everglades National Park provides stratigraphic control on the timing and mechanism of formation of enigmatic linear ridges.

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