GCGround Penetrating Radar Enhances Analogs*

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General Statement

Steeply dipping bedforms and bed sets often develop where sediment accumulates and migrates, and are expressed as clinoform patterns on seismic data. Ground-penetrating radar (GPR) provides ultra-high-resolution images of the internal structure of these sediment accumulations. Such images instruct the explorationist on the great complexity of these clinoforms accumulations and the potential for compartmentalization of a reservoir at fine scales.

Using GPR images of geologically recent sediments enables us to reconstruct the fine-scale process sedimentology, including changing current directions, bedform accumulation patterns and non-depositional and erosional events.

With this column we discuss GPR interpretations from two classic environments:

- The Pleistocene carbonate shelf of the south Florida-Caribbean region.

- The eolian linear dunes of the Namib Desert Sand Sea of west Africa.

The GPR data, recently acquired by teams of students and faculty from Brigham Young University, allow outcrop-scale interpretations of "seismic-like" waveform data that reveal what we might be missing in larger-scale seismic images of clinoform packages.

Examples

Carbonate Sediment Accumulations

The vast carbonate shallow-water platforms of the Bahamas represent one of the few laboratories where carbonate sedimentary processes can be studied in the modern realm, immediately adjacent to Pleistocene limestone formations preserved onshore.

Andros, the largest island of the Bahamas, is an ideal location for studying the internal structure of these deposits, where the accumulations of lime mud and ooid shoals have been integrated over long periods of geologic time.

A 400-MHz GPR survey on Andros was designed to target a single shallowing-upward depositional cycle, or parasequence (Figure 1a). Interpretation of the five reflective domains is guided by modern analogs of carbonate sediments on the Great Bahama Bank that borders Andros.

Given this context, we interpret the deep, poorly reflective interval ("a," Figure 1a) as low-energy, burrowed lime-mud lagoonal deposits with no expected internal bedding. The domain of low-angle clinoforms (domain "b") is interpreted as a migrational front that prograded lagoonward over a stabilized tidal flat.

This accommodation space ultimately was filled with less-ordered and more heterogeneous lagoon-fill peloids, skeletal grains and mud (domain "d"). The parallel (or sub-parallel) dipping reflector packages within domain "c" are interpreted as bankward-migrating ooid sand shoals that typically accumulate in shallow, high-energy tidal environments along the carbonate shelf margin.

Domain "e" is a muddier, less sandy deposit (confirmed by coring) interpreted to have accumulated in an abandoned tidal channel. This interpretation also is supported by the depth-slice through domain (Figure 1b), which cross-cuts both the underlying ooid shoal ("c") and migrational front ("b") facies.

Siliciclastic Eolian Dune Sediments

Linear sand dunes occur in large, low-latitude deserts in Namibia, the Sahara and the Arabian Peninsula. Winds blow oblique to the dune long axis, often with at least two different seasonal orientations that combine to transport sand parallel to the long axis. The dunes are 0.5-2.0 kilometers in width, often reach hundreds of kilometers in length and can be up to 100 meters in height.

200-MHz GPR profiles acquired along the flanks of large linear dunes in the Namib Sand Sea captured well-expressed bedforms. We show one GPR profile (Figure 2) that begins at the western base of a large linear dune, near the gravel of the interdune area, and continues up to the crest of the dune.

Two reflectivity intervals can be recognized:

- The upper interval consists of gently dipping planar reflectors that are well-layered and display a relatively uniform character. This interval mantles (or drapes) a thicker and more complex interval of shorter, steeply dipping reflectors that are separated by internal bounding surfaces. This upper interval represents a large 2-D superimposed, flanking dune that is oriented perpendicular to the linear dune, but is migrating parallel to the linear dune (into the field of view).

- The lower interval displays two patterns.

1) The bowl-shaped patterns are indicative of trough cross-stratification (TCS) produced by dunes with a 3-D wavefront moving approximately in and out of the cross section (i.e. parallel to the axis of the linear dune).

2) Tabular to sigmoidal patterns indicate 2-D dune fronts migrating approximately along the cross section (i.e. perpendicular to the axis of the linear dune). These two patterns frequently cross-cut each other, indicating active migration of superimposed dunes on the flank of the dune during this phase of deposition.

Although the GPR profile displays multiple migration directions for these superimposed dunes, the abundance of bowl-shaped TCS sets suggests a strong component of axis-parallel dune migration. The most prominent single reflector on the profile separates the upper and lower intervals – this surface displays a variety of reflection terminations including toplap, downlap and onlap (Figure 2). These terminations suggest that the reflector was a prominent erosional surface.

This surface thus delineates a major change in process sedimentology from an active dune migration phase below to a sediment-draping phase above. The various stratigraphic phases undoubtedly represent variable wind flow regimes over time as well as the evolving geometry of the linear dune as it grows and migrates.

Giant Foresets Formation, Taranaki Basin

Remember that the foregoing observations from GPR are at scales well beneath “sub-seismic.” Let us now consider a conventional seismic example on which analogous clinoform features are expressed.

The Giant Foresets Formation is a Plio-Pleistocene succession of fine-grained clastic sediments deposited on the marine shelf-to-basin margin of the northern Taranaki Basin, located offshore northwest of New Zealand. This formation is known for its well-expressed stacked, sigmoidal wedges of clinoform reflectors, and it contains topset, progradational or degradational foreset and bottomset reflectors (Figure 3).

These reflector patterns represent different facies on the continental shelf, slope and basin floor, respectively. Qualitatively, the patterns are similar to those on the GPR sections and likewise represent variations in the energy of the environment, depositional slope and wind or wave direction.

Conclusions

Lessons for the seismic interpreter learned from the GPR examples:

- Progradational and bedset patterns are scale-invariant on waveform data.

- Although the depositional environments in these examples are fundamentally different, clinoforms reflectivity patterns have much in common.

- Thus, much can be learned from studying fine-scale geological analogs using GPR.

- GPR data show how “hidden” fine-scale heterogeneity in sediment packages could affect flow and storage compartmentalization in a reservoir.

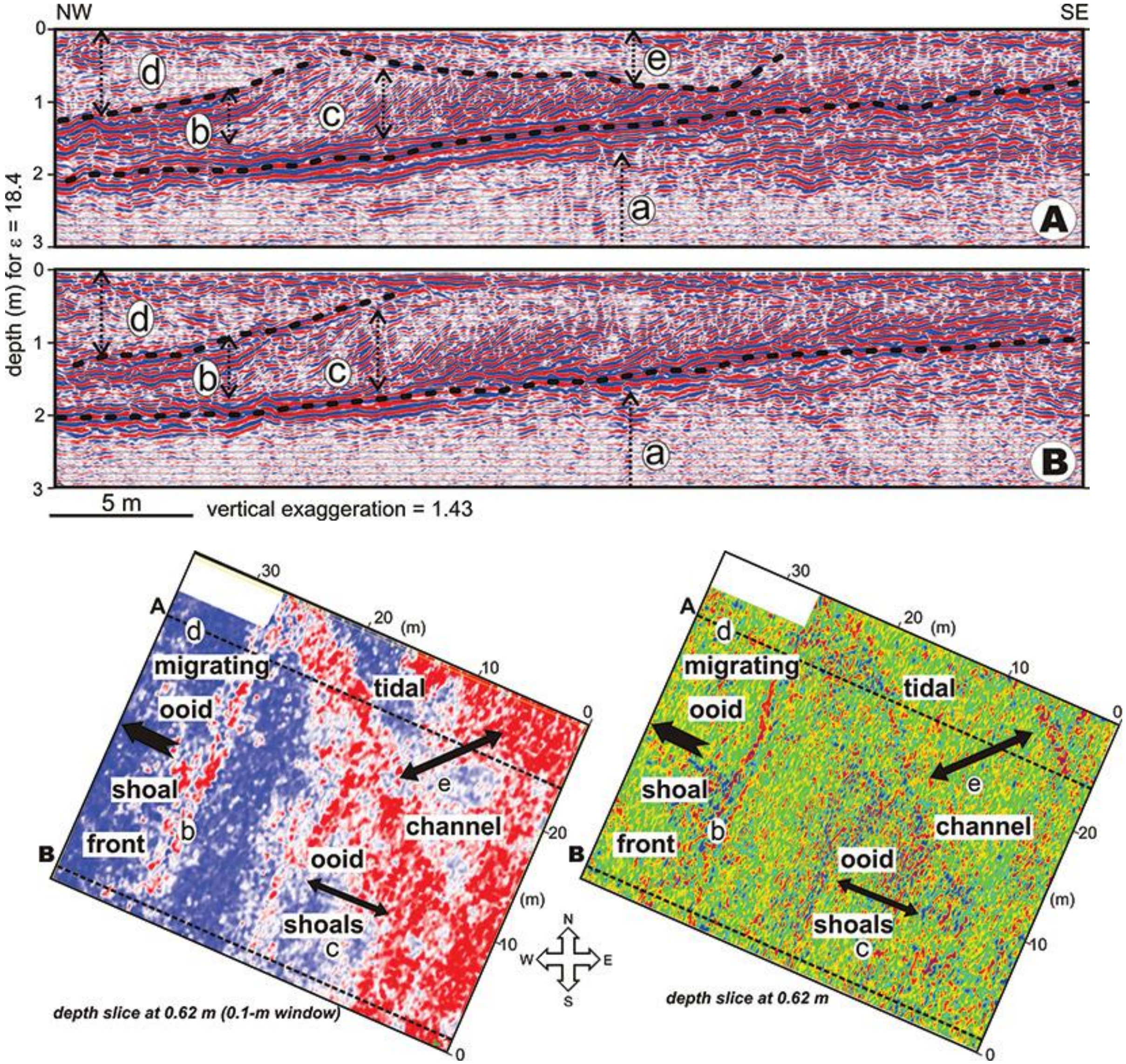

Figure 1. Left (a), 400-MHz GPR profiles from Andros Island. Letters indicate reflective domains referred to in the text and in Figure 1b. Depth conversion was based on a dielectric constant of 18.4 (0.07 m/ns). This provides a vertical resolution of 4-5 centimeters. These and subsequent profiles were processed using software generously provided by a Landmark (Halliburton) university grant. Middle (b), depth slice averaged over 0.1 m depth from GPR 3-D volume in Andros with location of profiles A and B noted; right, same as middle, but with no vertical averaging, which provides enhanced precision.

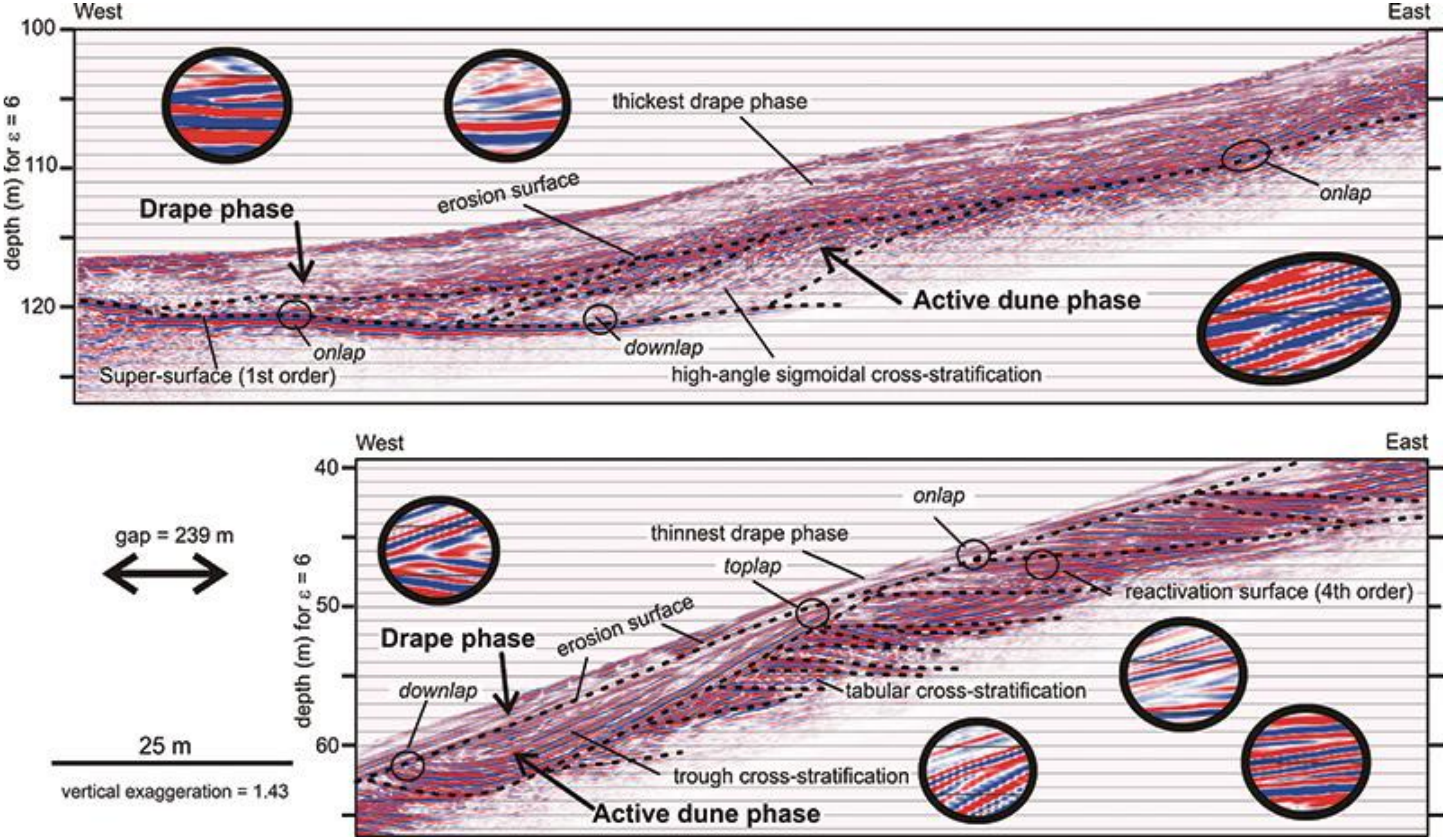

Figure 2. Excerpts of a 200-MHz GPR profile collected over the western flank of a dune in the Namib Desert. Excerpts of data are shown encircled. For depth conversion we used a dielectric constant of 6 (0.12 m/ns), yielding a vertical resolution of 15 centimeters. A dielectric constant of 6 is similar to values used previously for dunes in the Namib Desert and is consistent with a dry, quartz sand deposit.

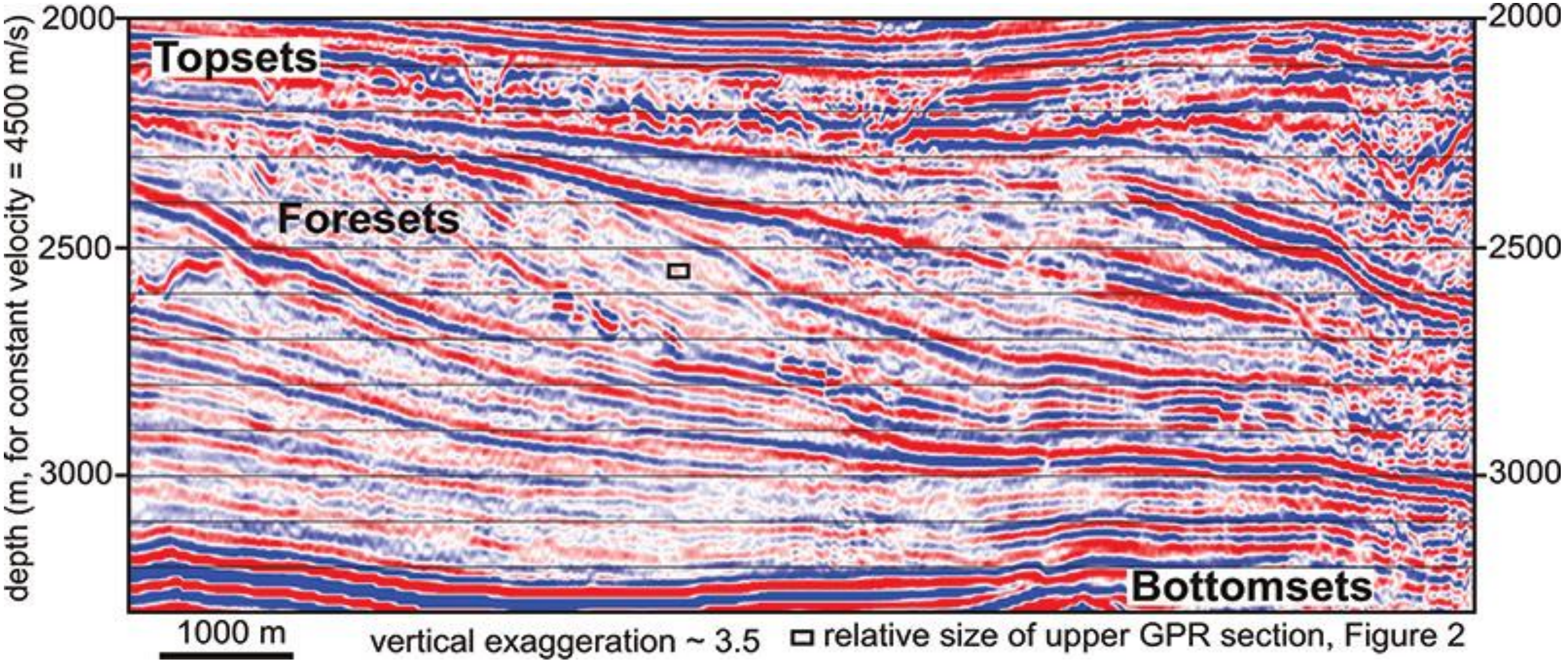

Figure 3. Excerpt from the 3-D Parihaka seismic dataset, Taranaki Basin, showing an example of the Giant Foreset Formation. For an assumed generalized velocity of 4500 m/s and an assumed dominant frequency of 50 Hz, the vertical resolution of the data is about 23 meters. Data set courtesy of Gerald A. Morton and Pogo Producing Company (now Plains Exploration and Production Company).