Journal of Applied Geophysics 81 (2012) 21–28

Contents lists available at SciVerse ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Constructing hydrocarbon reservoir analogues of aeolian systems using ground penetrating radar

D.I. Tatum [a,*], J. Francke [b]

[a] Institute of Petroleum Engineering, Heriot-Watt University, Edinburgh, UK
[b] International Groundradar Consulting Inc., Vancouver, Canada

ARTICLE INFO

Article history:
Received 27 October 2010
Accepted 15 September 2011
Available online 24 September 2011

Keywords:
GPR
Libya
Dune
Sand sheet
Analogue
Reservoir model

ABSTRACT

This paper presents a three-dimensional ground penetrating radar (GPR) case study of contemporary dunes from southern Libya that may serve as an analogue for oil and gas reservoirs in aeolian systems. A 30 MHz inline GPR system was used to image an undulating region 260 m wide × 480 m long in less than 4 h, with a line spacing of approximately 1 m at survey speeds of over 30 km/h. The internal aeolian architecture was imaged to a depth of about 40 m. Complex three-dimensional cross-stratification is evident within the resultant 3D data cube. A full range of dune heterogeneity is inferred: facies interaction between lake and dune environments, the course of ancient streams, dune field/sand sheet relationships, bounding surface geometry and primary strata type distribution. Different dune generations are perceived within the survey, with complex superimposed relationships apparent. Near-surface sand sheet and deeper linear dune/barchanoid ridge geometries are revealed. However, it is recognised that the complex pattern of contemporary dune formations in the area may indicate alternative interpretations. Finally, the distribution of appropriate reservoir properties is discussed.

1. Introduction

Aeolian dune systems have formed throughout the Earth's history. Ancient deposits have subsequently been buried and now form significant hydrocarbon reservoirs around the world. Characteristically, they have high porosity and permeability and good lateral continuity, forming reservoirs with varying degrees of complexity (Fryberger, 1990). In this paper, we discuss a ground penetrating radar (GPR) survey of contemporary dunes in southern Libya that may be used as an analogue to these ancient deposits and hence to these significant hydrocarbon fields.

The complex three-dimensional structure of dunes defines their spatial heterogeneity distribution which will affect reservoir behaviour, the impact of which often increases later in the life of a hydrocarbon field. In aeolian reservoirs, these heterogeneities occur at a range of scales. At the largest scale, this commonly results from the juxtaposition of aeolian sediments with fluvial, sabkha and lacustrine deposits; at the medium scale, the stacking patterns of cross-beds; whilst at the finest scale, the lamination of different stratification types (Sweet et al, 1996). Geological models, however, are usually constructed with a focus on the large scale correlatable features, which leads to an underestimation of heterogeneity, specifically at the bedform and lamina scales (decimeter to millimeter range).

Internally within dunes, bounding surfaces subdivide aeolian deposits into sets of cross strata. These surfaces represent dune migration episodes, periods of erosion, or changes in the depositional regime. Each bounded set represents a different period of deposition and, as such, may have different petrophysical properties to adjacent sets. Furthermore, the properties of these bounding surfaces may impact fluid flow between sets. In order to optimally manage petroleum reservoir development, the spatial arrangement of such bounding surfaces needs to be incorporated into subsurface models. However, adequate models cannot be obtained directly from the reservoir as no high-resolution imaging techniques exist for the inter-well area. At best, indirect inferences from an ensemble of remote data can be used to broadly constrain major features. However, many spatial parameters remain poorly constrained, particularly in 3D.

By mapping the 3D distribution of dune architecture, specifically at the fine and medium scale, it is possible to capture details of facies interactions, the extent of bounding surfaces and the distribution of stratification types (e.g. primary strata types: grainfall, grainflow, wind-ripple lamination). 3D models of different dune types may be captured, with the features typical to them mapped. If these dune types can be recognised and differentiated in a reservoir, for example from image logs, then geometries and typical distributions can be modelled, by analogy, away from well control. Data could then be upscaled and effective properties derived, for use in a coarser sector or full-field reservoir model.

1.1. Traditional analogue studies

One of the approaches to obtain such information is to use analogue outcrops (Gawthorpe et al, 1993). However, the results of such studies are rarely three-dimensional. Usually, the data are only

* Corresponding author at: Institute of Petroleum Engineering, Heriot-Watt University, Edinburgh, EH14 4AS, UK. Tel.: +44 131 451 3566; fax: +44 131 451 3127.
E-mail address: dominic.tatum@pet.hw.ac.uk (D.I. Tatum).

0926-9851/$ – see front matter
doi:10.1016/j.jappgeo.2011.09.014

two-dimensional for bed set scale and one-dimensional for lamina scale, as they are acquired from discrete intervals of vertical sedimentary logs taken along a cliff face. As a result, it is not possible to deterministically build a 3D geometry of individual sand bodies.

Shallow seismic surveys are able to capture some internal detail, but not at high enough resolution to resolve fine-scale heterogeneity (generally on a metre scale). The lithological components of many outcrop analogues have insufficient acoustic impedance contrasts for seismic reflection techniques to be feasible. GPR can have similar limitations if electrical impedance contrasts are too small (Brewster and Annan, 1994), or the overall conductivity is too large.

Hand dug trenches (McKee and Tibbitts, 1964), mechanical excavation (McKee, 1966), measurements of deflating dunes (Hunter, 1977) and numerical modeling (Rubin and Hunter, 1985) have all been attempted over the past 40 years. Although trenching may provide unsurpassed detail of the internal structure of a dune, the technique is limited by the shallow angle of repose for dry or damp sand, as well as the practical limit of digging. Furthermore, trenching is time consuming and provides only a small segment of data over a large dune or sand sea. Studies of the internal structure of a large dune or regional mapping of dune base topography would be unfeasible by mechanical means alone. As a result, scarce information on height:length:width relationships of typical aeolian sedimentary structures exists (Prosser and Maskall, 1993).

1.2. The use of Ground Penetrating Radar (GPR)

Over the past 20 years GPR has presented itself as a possible solution, imaging the 3D internal architecture of dune forms at a range of scales (Bristow et al., 1996, 2000, 2005, 2010; Derickson et al, 2008). The depth of a GPR investigation is controlled by the electrical and magnetic properties of the ground, and scattering of the radar energy by buried targets. GPR is most effective in regions which exhibit low electrical conductivity and low magnetic permeability, and are homogeneous on the scale of the radar wavelengths (commonly decimetres or meters) (Annan, 1999). These characteristics describe most sand dunes, suggesting that the GPR method is ideal for imaging their internal structure.

However, in practice, GPR technology suffers from a number of drawbacks which limit its effectiveness. GPR vertical resolution is proportional to the frequency bandwidth transmitted by the antennae and, generally, inversely proportional to the depth of penetration. That is, high resolution images may be acquired with high frequency antennae (e.g. 200 MHz), but with a loss of penetration. Conversely, penetration to 25 m or more may be obtained by low frequency antennae (e.g. 25 MHz), but at a considerable loss of resolution. Ideally, a survey seeks to select suitable antennae in a compromise between maximum resolution and a suitable depth of penetration for the purposes of the study.

Early work on Egyptian sands was conducted using rudimentary GPR equipment in the 1980s for archaeological investigations (Cook, 1974). However, the first application of the technology to study dune topography was conducted by Bristow et al (1996) in Abu Dhabi. Ground-truthing for their survey was accomplished by bulldozing a trench that enabled the complex bedding features noted in the GPR profiles to be interpreted as changes in dampness of the sands associated with subtle changes in grain size. Extensive tests have been conducted on the cause of reflections from GPR signals in sands (Bano and Girard, 2001; van Dam, 2001; van Dam and Schlager, 2000; van Dam et al, 2002). Their findings suggest that pore water content, related to variations in grain size, is the most critical factor, rather than geochemistry and the presence of organic matter. Each of these works has been restricted to the study of a single dune to depths not exceeding 30–35 m.

The application of GPR technology to imaging dune stratigraphy to create petroleum reservoir analogues dates to the mid-1990s (Knight et al, 1997; Thompson et al, 1995). These studies, including a more recent paper on the use of GPR to construct a 3D reservoir model from the Jafurah sand sea in eastern Saudi Arabia (Adetunji et al, 2008), were generally restricted to small survey areas, often only tens of metres per side, and limited to the penetration depth of the available GPR instrumentation.

1.3. Objective

It was our aim, therefore, to assess the capabilities of modern deeper imaging GPR technology to rapidly acquire a three-dimensional GPR dataset to significantly greater depths. The intention was to capture complex internal stratigraphic interactions and assess the full scale range of heterogeneities. These data can be used for petroleum system analogue modelling. To this end, we were successful, capturing details of facies interactions (palaeolake surfaces/palaeochannels), the extent of medium to large scale bounding surfaces (1st & 2nd order), and facilitating the distribution of smaller scale sedimentary structures (primary strata types) and their associated properties. These data were acquired with an integrated inline GPR/GPS system, with a centre frequency of 30 MHz, over an undulating sand sheet. A 260 m wide × 480 m long volume was imaged in less than 4 h, with a line spacing of approximately 1 m at survey speeds of over 30 km/h.

2. Instrumentation

Apart from the constraints on GPR system performance caused by geology, the limiting factors for radar system performance are the power of the transmitter, the sensitivity of the receiver, the geometry and frequency of the antennae and the ability of the GPR system to stack successive signals to improve the signal-to-noise ratio (Neal, 2004).

Commercially-available GPR instruments suffer from a number of drawbacks when considering their suitability for long-range rapid-areal coverage 3D surveys. Aside from the legislated limitations on transmitter power for low-frequency GPR systems, the unwieldiness of resistive dipole antennae and the need for fragile fibre optic cables, field laptops and external batteries render the acquisition of 3D GPR data over areas greater than a few hectares impractical. A true 3D survey with low-frequency antennae would require equal trace and line spacing, usually at 1 m intervals.

Regardless of logistical restrictions, commercial GPR systems are limited in their penetration depths in sand dunes. In most dunes where saline groundwater is not present, the maximum penetration of a radar system is determined by the noise floor, or the depth at which spurious signal noise overwhelms real reflections. Without lowering the frequency, this depth may be increased by increasing the transmitter power and/or the number of stacks.

Simply increasing transmitter power does not necessarily provide significant additional penetration. The radar range equation suggests that, in order to effectively double penetration, an increase in transmitter power of 16 times is required. As most commercial GPR transmitters have a peak voltage of approximately 500 V, a peak voltage of 8 kV would be required to theoretically double penetration. Such voltages would not be feasible due to the limitations of transmitter electronics and the likely signal saturation from near-field reflections in the receiver electronics. Indeed, high voltage transmitters marketed by GPR manufacturers generally compensate by lowering their pulse repetition frequencies.

The second approach to increasing penetration in environments where penetration is limited by the noise floor is by increasing stacking. Stacking 1000 times theoretically would double penetration over a single stack system. However, commercial GPR systems employ incremental time sampling, suggesting that 1000 stacks over a trace comprised of 512 data points would require over 5 s to acquire, not including processing and transmission overhead time. Such a slow survey speed would not be practical for large areal coverage.

In order to overcome these problems, a custom radar system (UltraGPR) has been designed, using real-time sampling and inline (colinear) antennae (in this case, with a frequency of 30 MHz). The