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Virtual Outcrops: 3-D reservoir analogues

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Abstract: Sedimentary architectures observed in 2-D outcrop sections are commonly used to build petroleum reservoir models. Advances in digital photogrammetry now allow the analysis of outcrop analogue aerial photographs, not only in three dimensions, but also dynamically. Digital photogrammetric techniques have also been adapted to close range photographs of well exposed cliff sections, to derive high resolution, bedding measurements in 3-D. Merging the aerial and terrestrial photogrammetric output with other data, such as shallow cores or Ground Penetrating Radar creates 3-D volumetric, Digital Solid Models (DSM) (see research website). A DSM can be extensively interrogated and the resulting meta-data used to construct 3-D, deterministic, reservoir models. Subsequent fluid flow simulations through these reservoir models can be animated, allowing identification of areas of interest or potential field management problems, such as by-passed hydrocarbons. Animations constructed from digital fly-throughs of these models communicate results from target outcrops, pinpointing areas of interest for follow-up field reconnaissance and better understanding of stratigraphy.

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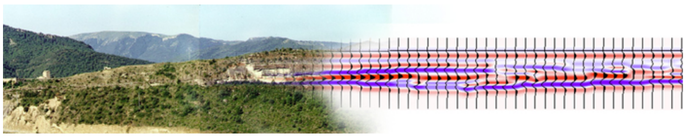
Introduction

The petroleum industry is increasingly looking for methods to reduce uncertainty in field development. It is important to have a quantitative understanding of the 3-D geometry, spatial distribution and petrophysical properties of genetic sedimentary units, in order to reliably appraise reservoir potential. Core and log data, while detailed, are insufficient for lateral interpretation over inter-well volumes, whilst seismic data typically have insufficient resolution to capture all the relevant sedimentary architecture.

Geologists assess the flow properties of petroleum reservoirs by studying analogous, large-scale sedimentary outcrops. One method of obtaining geometric information of sedimentary architecture is to acquire ground-based photomosaics of well exposed outcrop sections which, when combined with conventional sedimentary logs, are interpreted both sedimentologically and stratigraphically. This technique can be used on outcrops with little rugosity to acquire quantitative geometric data from sections tens of metres thick (Arnot *et al.* 1997). However, large-scale planar exposures are uncommon and photo-geological interpretations can suffer from distortions and parallax effects. Additionally, interpreted measurements taken from 2-D exposures may be influenced by the size, shape and orientation of the exposure, rather than by the dimensions and shape of original geological features (Geehan and Underwood 1993). Comparison studies generating synthetic seismic sections from 2-D photomosaic interpretations show the difficulty in resolving sedimentary bodies from seismic data in enough detail for successful characterisation (Figure 1).

Figure 1. Sand-rich turbidite channels



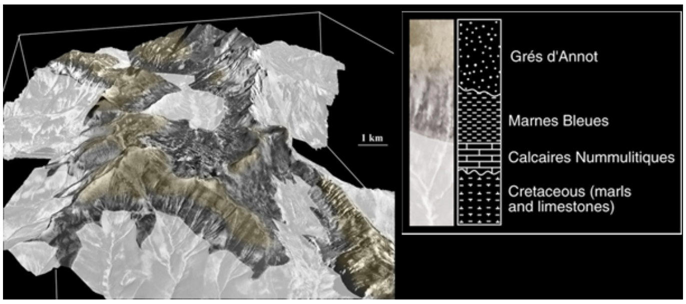
Exceptionally well exposed, sand-rich turbidite channels of the Upper Campodarbe Group, at Ainsa II, Southern Pyrenees, Spain have been interpreted and 2-D synthetic seismic sections have been constructed, with parameters honouring Tertiary reservoir rock properties in the UKCS. Seismic central frequency was set at 52 Hz.

Digital Photogrammetry

Historically, geologists used stereoscopes to study large-scale aerial photographs, as an aid to field reconnaissance (Pillmore 1989) and to map regional stratigraphic frameworks on well exposed geological outcrops (e.g. Sgavetti 1992; Lebel and de Roza 1999). Technological advances using analytical plotters interfaced with computers, could only generate Digital Elevation Models (DEMs) as the final product (Pringle *et al.* in review).

Digital photogrammetry, using VirtuoZo software supplied by Supresoft Inc., converts scanned aerial photographic images into 3D digital models. Digital Terrain Models (DTMs) are produced, which give more accurate representation of the topographic surface, with the image pixel positions re-projected to form a geographically referenced Ortho-Rectified Image (ORI) in 2D. The generation of ORIs from stereo photographs removes inaccuracies associated with lens distortion and other photographic effects, which is vital for accurate measurements. The ORIs are then draped over the interpolated DEMs to produce a three dimensional, high resolution, dynamic stereo-model (Figure 2). Multiple users can view the same image for example, by wearing polarised viewing glasses combined with a stereoscopic screen filter which covers the workstation screen (Figure 3). The 3-D model and rectified photographic imagery can then be shared with a wider, non-specialised peer group, none of whom need photogrammetric skills.

Figure 2. Photogrammetric mapping of stratigraphic boundaries



Photogrammetric mapping of stratigraphic boundaries in the Tertiary deep-marine sediments and underlying faulted Cretaceous basement in the Grand Coyer Sub-basin, SE France. The model has been interrogated for stratigraphic surfaces and large-scale fault geometries, then the ortho-rectified image has been appropriately coloured and re-imported into the stereo-model.

Figure 3. Photogrammetric mapping of 3-D digital models

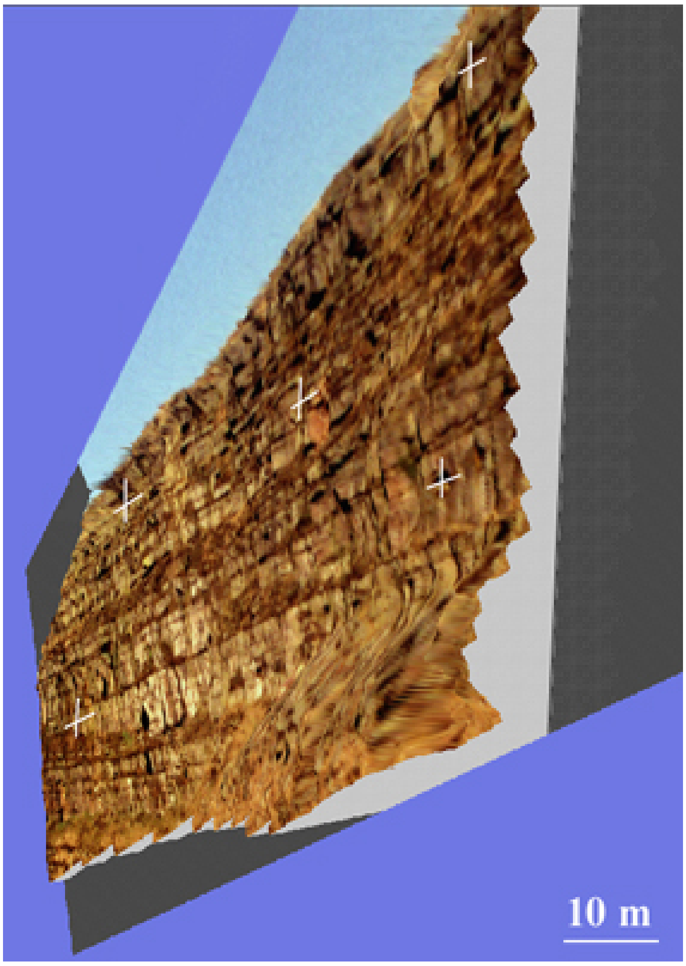
Photogrammetric mapping of 3-D digital models in action by team members. The models once completed can be viewed in stereo by use of a Nu-vision screen and polarised glasses, and can be freely rotated and viewed from any desired orientation.

Digital terrestrial photogrammetry

Digital terrestrial photogrammetry has been developed to create 3-D surface models of well exposed cliff sections of outcrop analogues. Ground-based, overlapping photographs are taken orthogonally to the cliff section, with control provided by standard surveying techniques, mirroring the aerial photogrammetric method (Pringle *et al.* in review). Figure 4 shows a surface model generated using this technique of Upper Carboniferous Shale Grit Formation turbidites in Derbyshire, UK. Once the model has been generated, it can easily be analysed in stereo from as many viewpoints as desired. A digitising option in the photogrammetric software allows rapid acquisition of sedimentological surface measurements in 3-D, to accuracies of a few centimetres. Cliff-sections may be studied from viewpoints that a ground-based geologist cannot occupy, e.g. along a plane parallel to bedding. This minimises potential interpretation errors and aids the correlation of sedimentary units.

The terrestrial cliff model shown in Figure 4 has been rotated to its correct geo-referenced location and merged with aerial photogrammetric data to create a Digital Outcrop Model (DOM). This has the advantage of combining top surface, regional geological features with detailed geology from vertical cliff sections.

Figure 4. Terrestrial photogrammetry 3-D digital model



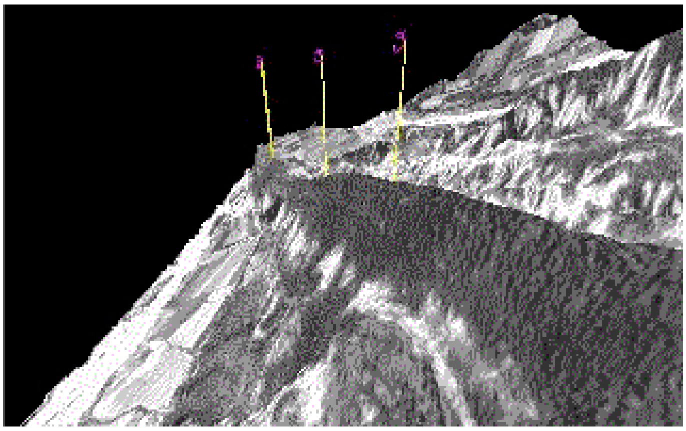
Terrestrial photogrammetry has produced a 3-D digital model of a cliff exposure of Upper Carboniferous, sand-rich turbidite deposits of the Shale Grit Formation, Derbyshire, UK. Total Station Points obtained using standard surveying techniques are shown as white crosses, which provide the control necessary for the photogrammetric software to produce the models.

Digital Solid Models

To become fully three dimensional, it is necessary to integrate volumetric data into the Digital Outcrop Model. This can be undertaken in a variety of ways. Xu *et al.* (2000) for example used surveyed control points to rectify cliff photographs, and integrated bore-hole and Ground

Penetrating Radar (GPR) data to produce a 3-D 'virtual outcrop' of a Cretaceous Austin Chalk outcrop, in Texas, US. Research shown here has correlated Upper Campodarbe Group sand-rich turbidite channel units near Ainsa, Spain, by integrating aerial photogrammetric output with shallow cores drilled behind outcrop faces. The exceptionally well exposed, turbidite channels form prominent ridges, which are clearly visible in the animation shown in Figure 5. Due to the complex topography, correlation of sandbodies by conventional mapping had proven to be difficult and time consuming. Accurate, photogrammetric measurements has been combined with the shallow core information to provide a 3-D stratigraphic framework of the area. The model can then be verified and refined by subsequent detailed field measurements.

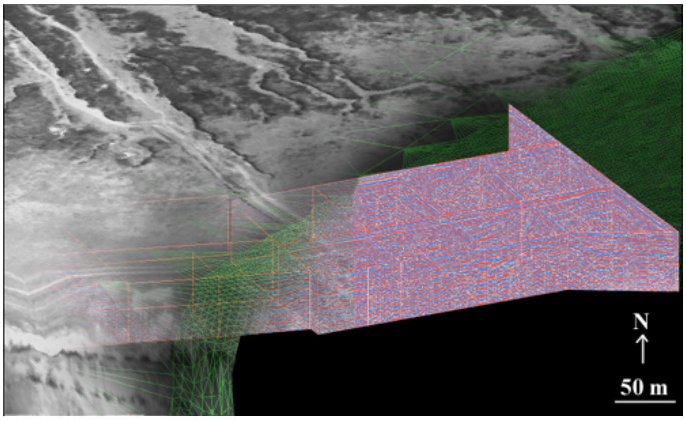
Figure 5. Animation fly-through over the Upper Campodarbe Group turbidite deposits, Spain



Animation fly-through over the Upper Campodarbe Group turbidite deposits, Spain near Figure 1. Aerial photogrammetric output has been combined with shallow core-log information derived from drilling behind outcrop faces.

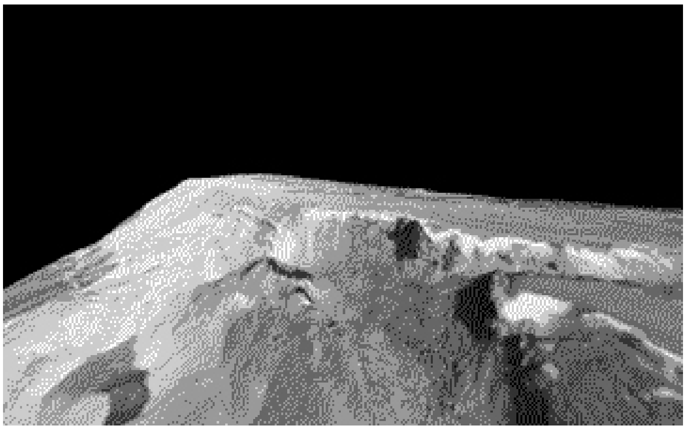
Ongoing internal research is utilising shallow geophysical techniques, in this case Ground Penetrating Radar (GPR) to provide 3-D volumetric data by imaging sub-surface geology (Pringle *et al.* 1999). A series of GPR profile in-lines and cross-lines were acquired over a study area in Derbyshire, UK. These profiles have captured the 3-D architecture of deep-water, sand-rich units exposed in the outcrop cliff section shown in Figure 4. The 2-D GPR profiles are integrated into the DOM to create the Digital Solid Model, shown in Figure 6. From integrating surface geological information and subsurface geophysical information, multiple palaeo-channels have also been interpolated. Figure 7 shows an animation fly-through of this model, generated in Bentley Microstation software, which allows visualisation of the complete field area, rather than a static view.

Figure 6. Digital Solid Model (DSM)



Multiple 2-D Ground Penetrating Radar (GPR) profiles have been incorporated into photogrammetric output to create a Digital Solid Model (DSM) of the Upper Carboniferous, turbidite deposit in Derbyshire, UK. The DSM has been partially removed to show the underlying DEM (green) and GPR (red and blue lines) data.

Figure 7. Animation through the Derbyshire DSM

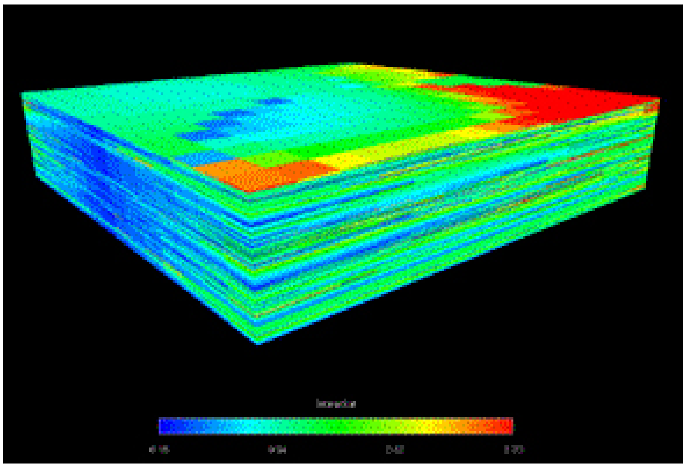


Animation through the Derbyshire DSM, shown in Figure 6. GPR profiles are shown as the multi-coloured, slices viewed beneath the outcrop surface, with the brown lines indicating the interpolated, sub surface palaeochannels.

Flow simulations

DSMs can be analysed, either for stratigraphic or sedimentological horizon mapping, or for 3-D geobody description. The resulting three dimensional data can be used to construct realistic 3-D reservoir models. These deterministic models can be analysed for sandbody architecture (e.g. channel sinuosity), connectivity between geobodies or act as a reference for modellers to validate their model simulations. Figure 8 shows a fluid flow simulation through a reservoir model of a heterogeneous, turbidite sand-sheet system. The model is based on an outcrop analogue in the French Alpine region, and it was built with Roxar's IRAP RMS software. Animations allow a much better understanding of flow paths and the identification of problem areas, for example zones of by-passed hydrocarbons.

Figure 8. Simulated fluid flow by injector/producer well pairs

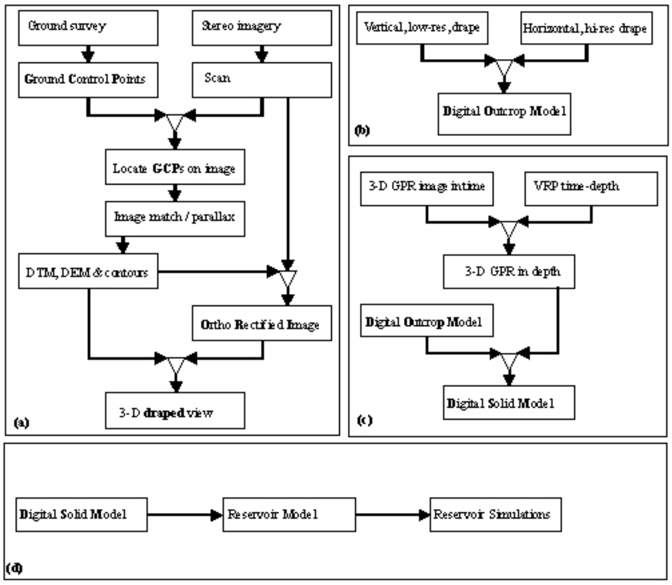


Animation shows simulated fluid flow by injector/producer well pairs through a 3-D turbidite, sand-rich sheet system, petroleum reservoir model. The reservoir model has been constructed in Roxar RMS software using a combination of field work, aerial photogrammetry and constrained to analogue reservoir poroperm characteristics. The model was then exported to ECLIPSE software, where the simulations were undertaken.

Workflow overview

Figure 9 shows the workflow overview, summarising the steps undertaken to reach the flow simulation stage. Several software applications and hardware platforms are used. Deterministic reservoir models derived from 3-D outcrop analogues, realise a quantum leap in field geological acquisition.

Figure 9. 4-stage workflow



4-stage workflow that is utilised for this research: a) digital photogrammetry creates: a Digital Elevation Model, an Ortho-Rectified Image and a 3-D draped view; b) integration of aerial and terrestrial photogrammetry forms a Digital Outcrop Model; c) insert 3-D volumetric information (eg. GPR) to form a Digital Solid Model and; d) construct a petroleum reservoir model from interrogation of the DSM, then undertake fluid flow simulations on the model.

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