Virtual outcrop models of petroleum reservoir analogues: a review of the current state-of-the-art

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Introduction

A subsurface reservoir model is a computer based representation of petrophysical parameters such a porosity, permeability, fluid saturation, etc. Given that direct measurement of these parameters is limited to a few wells it is necessary to extrapolate their distribution. As geology is a first order control on petrophysics, it follows that an understanding of facies and their distribution is central to predicting reservoir quality and architecture. The majority of reservoir modelling systems used for the subsurface are based on correlation of seismically-derived surfaces to define reservoir zones. Well data are then used to define further, sub-seismic scale horizons and determine the zone properties which are represented in grid cells. Understanding the distribution of both sub-seismic surfaces and potential heterogeneous geology between them remains a significant challenge. Furthermore as the typical grid cell size is c. 50-200 m^2 it is challenging to incorporate small-scale heterogeneities. It is critical, therefore, to use realistic values for both key stratigraphic horizons and internal facies distributions.

Depositional facies is a fundamental control on petrophysics. However, facies scale heterogeneities are not resolvable using current seismic methods, and well data provide little or no data on 3D geometries beyond the well bore. Studies of modern sedimentary events can give some indication of the link between depositional processes and facies distribution (e.g., Kenyon et al., 1995); however preserved depositional architecture is also strongly controlled by changes in accommodation through time (Jervey, 1988). Laboratory-based experiments (e.g., Kneller & Buckee, 2000) and process-based modelling (e.g. Aigner et al., 1989; Peakall et al., 2000) further illustrate the link between depositional mechanism and facies architecture. However, such models are typically on a scale that is far smaller than the typical field and are more applicable to upscaling studies (Nordhal et al., 2005; Ringrose et al., 2005).

Outcrop studies have long been employed as a mechanism of studying analogues and understanding petroleum fields (Collinson, 1970; Glennie, 1970; Breed & Grow, 1979). Once the type of depositional system and the accommodation history of a hydrocarbon field are derived from subsurface data, appropriate outcrop analogue(s) can then be identified (e.g. Alexander, 1993). Suitable analogues are those that are geologically comparable to the system that is being studied and also have excellent 3D outcrop exposure over an area that is large enough to capture the scale of heterogeneity required (Clark & Pickering, 1996). Outcrop analogue studies are thus a key way of improving understanding of reservoir facies architecture, geometry, and facies distributions.

Outcrop analogue studies have been undertaken both qualitatively and more recently quantitatively. Traditional quantitative studies (e.g., Dreyer et al., 1993; Chapin et al., 1994; Bryant & Flint, 1993; Clark & Pickering, 1996; Reynolds, 1999) have been focused on the collection of outcrop data to populate inter-well reservoir model areas by stochastic, object-based methods (Floris & Peersmann, 2002). However, it can be difficult to extract usable data from traditional outcrop studies, especially when it needs to be integrated with petroleum engineering databases or to be visualized in 3D. Furthermore, outcrops which represent a topographic cut through solid geology are 2D and while rare examples show multiple sections through the solid geology with different orientations, geological expertise is still required to fully understand and interpret the 3D nature of the bodies. Such work may also need geostatistical data manipulation to overcome outcrop orientation and size issues (Geehan & Underwood, 1993; Vissa & Chessa, 2000) but ideally the data should be reconstructed in 3D. Accurate 3D reconstruction is the only way that parameters such as channel sinuosity, connectivity, and continuity of target sandbodies in 3D may be defined. Such parameters are a key control on hydrocarbon production, including sweep efficiency (Pringle et al., 2004a; Larue & Friedmann, 2005). Software for representing geology in 3D is routinely used to model subsurface reservoirs. This paper will show

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how recent digital data capture technique advances aids the interpreting reservoir geologist by obtaining accurate and quantitative outcrop analogue datasets to aid and perhaps modify his reservoir model.

Data collection methods

Techniques employed for the study of sedimentary reservoir analogues at outcrop have evolved from traditional geological mapping and recording of traditional sedimentary logs (Barnes & Lisle, 2004), to scaled measurements obtained from 2D photopanels (Arnot et al., 1997) to 3D outcrop reconstruction. Sample and section location has moved from simple triangulation to the routine use of hand-held GPS (Bryant et al., 2000) to the integrated approaches of today that use an ever expanding range of digital data acquisition techniques. Modern techniques allow rapid acquisition of ever more accurate and denser digital datasets from outcrop analogues (see Pringle et al., 2004b; McCaffrey et al., 2005). An overview of current digital data capture techniques (Table 1) with case study examples is now outlined.

Low/medium technology digital surface generation methods
Digital aerial photogrammetry (Pringle et al., 2004b for detail) generates a comparatively large-scale digital surface framework of a study area that other field-derived data (e.g., sedimentary logs, palaeocurrent data, other key stratigraphic/structural positions) can also be integrated into. Photogrammetric methods semi-automatically generate 3D Digital Terrain Model (DTM) surfaces, using overlapping aerial photograph stereo-pairs and ground control points as input. As an example, an 8 km x 12 km study site in the Champsaur region in the French Alps, a succession of Oligocene Grés du Champsaur turbidite units is exposed. Fourteen 1:17,000 scale, aerial photographs were combined with ground control points to generate a 4 m resolution DTM with a draped, ortho-rectified image (Figure 1). The resulting digital surface model, which took a few days to create, was analyzed to remotely and rapidly trace both key stratigraphic and structural surfaces. Subsequent detailed fieldwork on selected localities confirmed surface positions. Structural and sedimentological data were then integrated into the digital dataset (Brunt, 2003). The digital model was created within industry standard commercial reservoir modelling software so can be directly compared to sub-surface reservoir models. Once created, the model could have further digital data added and/or be used as a 'virtual field trip'. The main drawback of digital aerial photogrammetry is that the resolution is usually not good enough for detailed outcrop studies (Table 1). Near-vertical cliff-faces are also poorly resolved using this technique.

For actual field-derived measurements, recording of single xyz georeferenced datapoints during fieldwork can be carried out using a Global Positioning System (GPS) receiver. Until recently, hand-held systems were relatively inaccurate, especially in the z plane (altitude). Recent developments such as the WAAS (North American), EGNOS (European), and MSAS (Japan) augmentation systems, have led to satellite signal correction that has significantly improved location accuracy (typically to 1-5m) (see http://www.esa.int/esaNA/egnos.html; www.tracklogs.co.uk), making simple, cheap hand-held systems effective. It should be noted that Z accuracy is still poor (typically >10 m). However, this is not a significant problem if co-ordinate points are positioned on a DTM (for example, using the 4 m resolution Champsaur DTM – Figure 1) or if a stratigraphic datum rather than altitude is used for subsequent modelling (see later). Greater positional accuracy is obtained with differential GPS (dGPS) in which a base station receiver is left in a fixed position throughout surveying. The apparent base station drift is subtracted from the roving GPS unit position. The dGPS correction can be made during surveying via a radio link (termed real-time kinematic or RTK) or during post processing. These methods can be used to obtain very accurate positional measurements, typically 0.05 - 0.1 m depending on local site conditions and overhead satellite positions.

The new generation of dual-frequency (L1 and L2 datastreams) RTK dGPS systems allow users to collect xyz measurements with mm-accuracy (post processing), and readings may be taken in continuous real-time, with specified time or distance intervals and/or at points selected by the user. For example, in a 20 km x 40 km study area in the Tanqua Depocenter, SW Karoo Basin, South Africa, a succession of five sand-rich submarine fan systems within the Permian Skoorsteenberg Formation 400 m thick is exposed (Hodgetts al., 2004). A series of key stratigraphic (fan tops and bases) and structural (faults) surfaces were RTK dGPS surveyed on foot over large distances (>10 km daily). The resulting processed RTK dGPS points were then integrated with outcrop and borehole data to create highly detailed digital geological (stratigraphic and structural) models (Hodgetts

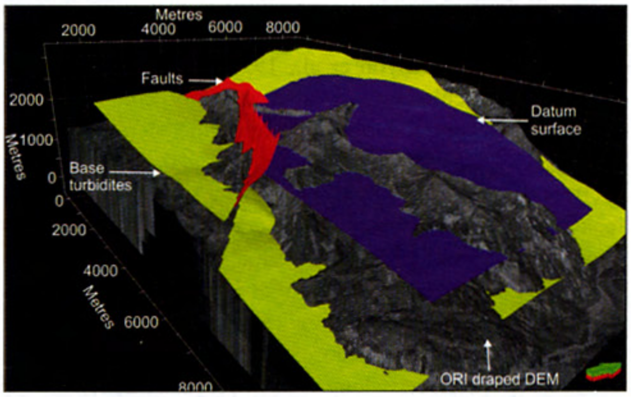

Figure 1 *Digital outcrop model of the Oligocene Grés du Champsaur turbidite sub-basin, SE France, produced by digital aerial photogrammetry. An accurate Digital Terrain Model (DTM) and draped rectified image were created from aerial photograph stereo-pairs and ground control points. Resulting model was interrogated by mapping onto the DTM for key stratigraphic and structural horizons before being verified by subsequent fieldwork.*

et al., 2004) based on a well constrained understanding of the stratigraphic evolution and distribution of facies and sandbody architecture in 3D (Hodgson et al., 2005) (Figure 2). Detailed, ground based surveying was required as key stratigraphic boundaries were rarely represented by a sharp contact that could be remotely identified (e.g. from aerial photographs). Sedimentary architecture, e.g., channel erosion surfaces and sandstone/shale bed lengths, were also surveyed using a combination of RTK dGPS surveying and total station work. These geometries can then be used as a database for subsequent stochastic modelling within the stratigraphic framework.

All forms of GPS systems are dependent upon receivers having line of sight with overhead satellites. Typically more

Digital data collection method	Typical accuracy	Typical application	Advantages	Disadvantages	Typical Cost
Aerial digital photogrammetry	~5-25m	Mapping large-scale stratigraphy & generate digital model framework	Fast, usually third-party acquisition (minutes); large areas covered & fast remote mapping (days)	Slow time processing (days); relatively low resolution & poor on near-vertical outcrop faces	High if survey has to be commissioned. Cheap if existing photos are used
Ground-based digital photogrammetry	~0.1-0.5m	Detailed study of complex outcrop faces	Fast acquisition (minutes); less detailed fieldwork needed	Medium time processing (days) & interpretation	Relatively cheap £600
Calibrated photo logs	~0.2m	Rapid collection of facies thickness and relative surface positions from cliff sections	Fast acquisition (minutes), Fast processing (hours) & rapid model creation	Can suffer from photograph distortion, no high resolution logging	Very cheap £300
Hand-held GPS	~1-5m	Sample point location & regional mapping	Instant locational fix	Significant 'Z' positional error (up to 30m)	Very cheap £150
RTK dGPS	Better than 10mm	Attribute collection, surveying outcrops & accurate base stations	Instant point collection allows 'walking out' of key surfaces, medium time processing (typically a day)	Not possible on near-vertical cliff-faces	Expensive £20ks+
Reflectorless Total Station	3mm at 200m range	Attribute collection, surveying outcrops, good for vertical faces	Instant point collection, data capture on near-vertical cliff faces	Slow to acquire, dGPS data needed to convert to UTM co-ordinates	Moderately expensive £2k
Ground-based LIDAR (laser scanner)	5mm at 200m range	Very rapid collection of outcrop surface topography	Relatively rapid acquisition (minutes);	Significant post processing (days)	Expensive £100k
Bore-hole data	1mm (from core)	Drilled behind outcrop to extend horizons into 3D	Very high resolution data, comparable to outcrop information & reservoir logs	Very slow acquisition (weeks), processing and interpretation (weeks)	Very Expensive £200k +
Near-surface geophysics (GPR in this case)	~0.1-0.5m	Acquired behind outcrop to extend correlated horizons into 3D	Allows 3D information behind outcrop to be acquired	Slow acquisition (days) and processing (days), only works in specific site conditions	Moderately expensive £30k

Table 1 *Summary of discussed outcrop analogue digital data collection methods (adapted from McCaffrey et al., 2005).*

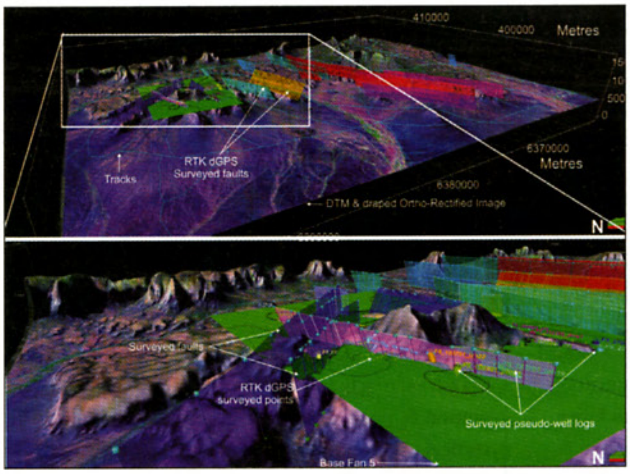

Figure 2 *Digital outcrop model dataset of Permian submarine fans from the Tanqua depocentre, SW Karoo Basin,, South Africa. Accurate 3D geological models were constructed for 3 basin floor fan systems. Input data included; Digital Terrain Model, RTK dGPS surveyed key horizons/faults and pseudo-well logs (see Hodgetts et al., 2004 for details).*

than five satellites are required to reduce positional errors. Some current RTK dGPS systems incorporate radio signal 'repeaters' that further increase range by boosting the base station signal, thus reducing the need to move reference receiver stations. In the near future measurement accuracy and area coverage will further improve as the next-generation L2C and L5 data stream frequencies from the US-based GPS and proposed European GALILEO satellite systems come into service.

Despite the detailed advances, GPS datapoint positional accuracy is still greatly reduced in areas such as deep canyons, close to large cliffs or in thick vegetation where there is a limited view of the sky. Modern dGPS systems refuse to obtain datapoints where location errors are too large (typically over +/- 0.2 m) although this information can be downloaded and discarded if necessary during processing. Difficult areas can be conventionally surveyed (such as the use of laser range finders and total stations). These techniques are also useful in acquiring quantitative data from inaccessible outcrops, especially if a reflectorless laser system is used. Conventional surveys are slow to acquire, requiring GPS surveying if resulting datasets need to be converted to real-world UTM co-ordinates. Some RTK dGPS systems have survey laser extensions that can acquire co-ordinates from locations that do not have satellite coverage.

Emerging ground-based terrestrial photogrammetric software can be utilised where accuracy and precision are less important than speed and collection of large volumes of surveyed data (Table 1). This method uses high-resolution digital camera images of an outcrop taken from various locations calibrated with a number of surveyed outcrop measurements. The images are combined to create accurate (typically 0.1 m spaced), coloured, digital surface models. For example, a 100 m x 40 m outcrop face in the Gulf of Suez had exposed a Tertiary Nukhul formation sedimentary succession of tidal-channel and tidal-flat alternate dominated intervals. Quantitative data on thickness variations and channel geometries help to define width/thickness relationships for the alternate intervals. ~200 digital photographs were taken ~10-50 m from the outcrop; software then combined 20 selected images to create a digital surface model (Figure 3). Once converted to real-world (UTM) co-ordinates, the digital surface model was used both to extract quantitative data and as a stratigraphic framework to place field data (digital

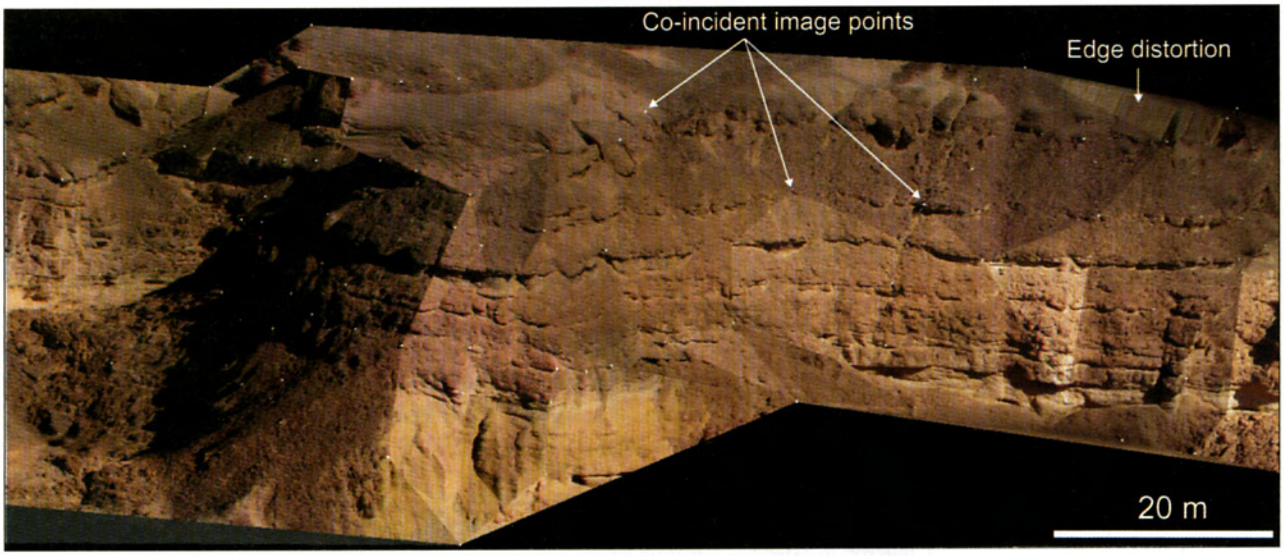

Figure 3 *Digital surface model of Tertiary tidal-flat and channel sediment succession, Nukhul Formation, Gulf of Suez, Egypt. 20 photographs taken 10-50 m from the cliff-face at different locations have been integrated within software using coincident points (marked) to create a Digital Terrain Model and lens-corrected, draped image. The resulting model was used as a stratigraphic framework to integrate other field datasets.*

sedimentary logs, palaeocurrent data, bed attitudes, etc.). The resulting integrated dataset was used to condition an outcrop based reservoir model employing an object based modelling approach.

High technology digital surface generation methods

Of the emerging survey hardware for close-range outcrop digital data capture, ground-based LIDAR (LIght Detection and Ranging) or laser scanning, is becoming the preferred technology. Very rapid xyz co-ordinate data point clouds are acquired from a scan position up to 1 km from the outcrop. Data volumes are large (up to 12,000 points per second), and data accuracy is high (kleiner dan5 mm under optimal data collection conditions) (Table 1). Multiple scans from different orientations are typically acquired for an outcrop to obtain full coverage of rugose surfaces. Resulting data point clouds can comprise over 10 million points (~1 cm spaced) on a 50 m x 100 m outcrop. Data point clouds are post-processed into real-world co-ordinates if scan tie points and/or LIDAR scan positions are accurately surveyed. Each datapoint has an associated reflection intensity value (a function of distance and target reflection) with newer LIDAR instruments having integrated high-specification digital cameras. Acquired images have known positions in relation to the point cloud and are used to colour code data points with RGB (Red, Green, Blue) values to give almost photographic quality scans. In cases where the camera-mounted digital images are at a higher resolution than the point cloud, the point cloud is re-sampled into a vertex-based, triangular mesh surface that has the lens-corrected image texture mapped onto it. The pixels in the draped image effectively fill any point cloud gaps. The completed digital mesh surface is still accurate and very flexible and has the bonus of having a much reduced digital file size (typically more than 20 times less than input point clouds).

Outcrop analogue LIDAR survey examples range from relatively large-scale stratigraphy studies (Bellian et al., 2005) to small-scale outcrop fault and fracture distribution studies (Clegg et al., 2005). At Mam Tor, Derbyshire, UK, a 500 m x 100 m exposure of sheet turbidite sandstones from the Carboniferous Shale Grit Formation was surveyed from one scan position ~150 m from the outcrop. This acquired 1.4 million datapoints over a seven minute survey period (Figure 4). The resulting data point cloud was rotated to view along depositional strata, 3D polylines representing sedimentary geometries and bed width/thickness measurements were then extracted.

At present, interpreted 3D poly-lines are generated directly from point cloud data. The intervening, texture-mapped surface segments are then interpreted for lithology and ground-truthed in the field. The sheer size of resulting datasets is hard to visualize and manipulate, even using high-specification computer hardware. Several days of processing is typically needed to convert point clouds to surface meshes which are easier to analyze and convert to user friendly data formats (Bellian et al., 2005). Emerging airborne LIDAR systems are capable of logging the complete waveform of the return laser pulse including intensity. Until recently only a few (first and last) of the returns from an output pulse were logged. This extra information has proved helpful in the remote classification of targets such as tree type and, with research, may be utilized in the remote, semi-automated detection of rock boundaries and lithologies from LIDAR point clouds.

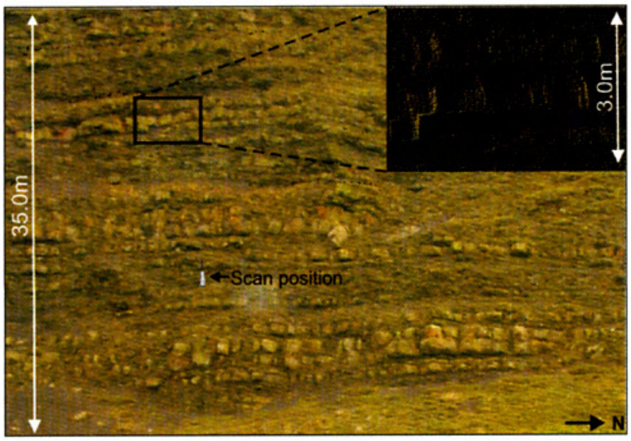

Figure 4 *LIDAR survey RGB coloured point cloud of the Carboniferous Shale Grit Formation at Mam Tor, Derbyshire, UK. Scan position is shown. Inset shows individual XYZ data point detail with an associated colour value (see text). Sedimentary geometries were extracted from the dataset.*

All of the detailed methods create digital surface models of outcrop analogue study sites which then have important geostatistics extracted. However, truly three dimensional detailed outcrop analogue data can only be extracted if subsurface data can also be acquired.

High technology near-surface methods

Shallow near-surface wells have been drilled behind outcrops in a few studies in order to constrain 3D changes of the geology behind cliff-faces (Browne & Slatt, 2002; Pickering & Corregidor, 2005; Hodgson et al., 2005). Such data are commonly used to both improve the link between outcrop and subsurface data and to provide a direct comparison between typical oil field data (such as cores and well logs) and the outcrop. As an example, seven research boreholes totalling 1274 m of core and a full suite of well log data (including FMI) were collected from the Tanqua Depocentre and integrated with detailed outcrop studies (Hodgson et al., 2005) However, whilst very high-resolution, these studies do not provide direct data on 3D sedimentary architectures.

High-resolution, near-surface geophysical data has the advantage of sampling a comparative large area behind outcrop cliff-faces given the right site and ground conditions (Table 1) which can be integrated into digital surface models. Shallow seismic data have been acquired behind outcrop cliff-faces, but usually with little success, chiefly due to the cemented nature of the sediments providing little or no acoustic impedance contrast between different sedimentary intervals (Coleman et al., 2000). Typically relatively thin target zones are still below near-surface seismic resolution. Ground Penetrating Radar (GPR), however, uses frequencies that are an order of magnitude higher than shallow seismic (100-1000 MHz compared to 1-200 Hz ranges respectively). This increase in frequency results in increased resolution (resolving ~0.1-0.5 m beds depending on specific GPR frequency). GPR reflection amplitudes are controlled by electro-magnetic property changes at lithological boundaries rather than by acoustic impedance. GPR is being increasingly used to acquire high-resolution, near-surface datasets on outcrop analogues (Young et al., 2003; Jol et al., 2003; Staggs et al., 2003; Pringle et al., 2003). Modern GPR studies use cut-away sections to compare sedimentary horizons with sub-surface reflection events (Bristow et al., 2000). In a similar fashion, Vertical Radar Profiles (VRPs) acquired down outcrop cliff faces allow GPR reflection events to be definitively correlated with observed cliff-face sedimentary horizons (Pringle et al., 2004a). VRPs also provide velocity calibration and identify multiple reflection events, much as VSPs do for seismic surveys.

Coastal cliff sections of the Carboniferous Ross Formation in Western Ireland, expose sheet-like turbidite sandstones and small-scale channels (typically 50-300 m wide) with heterogeneous fills (Figure 5). Study sites prove ideal for GPR data acquisition due to a lack of overburden, relatively shallow (kleiner dan 10 m) target and good dielectric contrast between target channel-fill intervals and sheet sandstones (Pringle et al., 2003). A high-resolution 3D GPR dataset was acquired across the Bridges of Ross study site between two outcrop cliff-faces (Figure 5) exposing heterogeneous intra-channel fill. Resulting horizon interpretations traced both discontinuous shale and inclined mudstone-clast conglomerate horizons in 3D that created small-scale deterministic models of channel-fills that were used to populate reservoir-scale turbidite reservoir models.

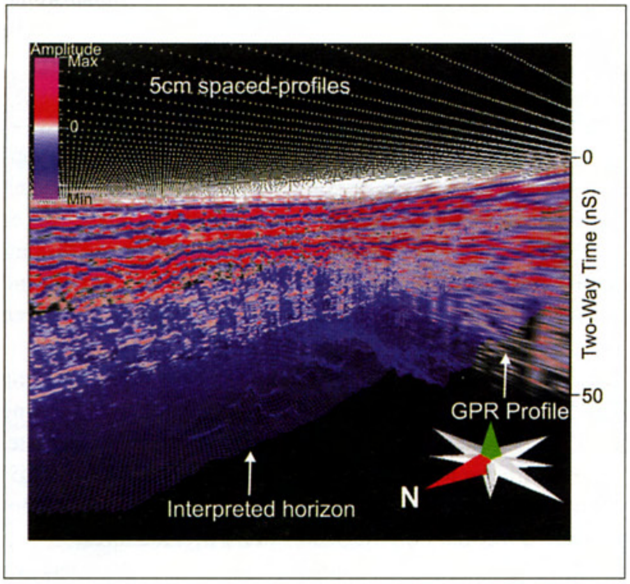

Figure 5 *High-resolution, pseudo-3D GPR dataset screengrab from the Carboniferous Ross Formation at the Bridges of Ross study site, County Clare Western Ireland. Heterogeneous turbidite channel-fill were traced in 3D between outcrop cliff-faces (see Pringle et al., 2003 for details).*

Current GPR hardware uses set dominant frequency antennae to acquire data, lowering frequencies typically increases penetration depth but at the cost of resolution. The 450 MHz dominant frequency antennae used in the detailed Ross study typically resolved reflectors 0.1 m apart down to 5 m below ground level. Emerging multi-frequency GPR equipment with automated integration of RTK dGPS positioning hardware should greatly speed up data acquisition. However, fieldwork time is significant; the Ross detailed study taking eight full field days to just acquire the GPR data.

Data integration, analysis and model building

It is necessary to process, integrate, and analyze the various digital data that have been collected. Data may include georeferenced 1D outcrop and well logs, 2D photo-panels and sedimentary horizon interpretations; 3D data including GPS or RTK dGPS surveyed xyz datapoint clouds; digital aerial and/or terrestrial photogrammetric output; and ground-based LIDAR survey data point clouds and texture mapped surfaces and near-surface data which may include well logs and/or geophysical datasets with interpreted horizons. Software designed for modelling subsurface reservoirs is currently the most suitable for integrating 1D, 2D, and 3D outcrop and subsurface data. This also provides a direct link to the subsurface geologist and reservoir engineer. Once processed, digital data can be imported into specialist software as pseudo-well logs (sedimentary logs), point sets (surfaces and faults), polygons (faults), or draped images onto surfaces. GPR data, for example, can be treated in the same way as seismic data (being SEG-Y format). Pringle et al., (2004a) details one such study integrating a variety of surface and near-surface datasets on a study site at Alport Castles, Derbyshire, UK. Carboniferous sheet turbidites and sandstone-filled channels are exposed on a ~400 m x 50 m outcrop. A detailed sedimentary, survey and photogrammetric study was completed. A near-surface GPR dataset was also acquired behind the outcrop, all digital data were then integrated into a single digital model using commercial reservoir modelling software (Figure 6). Sedimentary architectures, facies proportions, and bed geostatistics were extracted, reservoir uncertainty studies then showed connectivity under-estimated and channel sinuosity over-estimated only using 2D datasets (Pringle et al., 2004a).

Virtual outcrop models can also be populated with facies based petrophysics and flow simulated to improve understanding of the effects of sedimentary architecture on fluid flow with reservoirs as they are built within reservoir modelling software. For example, in an outcrop modelling study of two Cretaceous deltaic systems from Utah, USA, the effects of dipping clinoforms on simulated fluid flow was investigated (Figure 7). Data were collected as scaled photo panels which were used to create pseudo-well logs which were then loaded into the modelling system. These logs were used to create a series of close to deterministic geo-models in which petrophysical properties were assigned to the different facies. These models were then flow simulated to investigate a number of parameters such as the effects of clinoforms on flow, the different strategies for modelling clinoforms, the production from highstand and lowstand delta systems, and the preferred water flood direction vs. clinoform orientation (Howell et al., in press). In all cases the engineering, fluid and petrophysical properties were kept constant between the models and the flow simulation becomes a direct measure of comparative heterogeneity.

Once the sedimentary outcrop analogue digital model has been completed, post-depositional structural deformation may need to be removed from collected data so that original sedimentary architectures can be extracted for input into reservoir models or compared and combined with other outcrop analogue datasets. Alternatively, sedimentary systems can be modelled with reference to a datum surface, thus removing much of the need for structural restoration. The Middle Eocene Ainsa turbidite basin in the Southern Pyrenees, Spain has been digitally mapped with key stratigraphic horizons created in 3D (Figure 8) before being structurally restored to their original sedimentary position using commercially available software (Fernandez et al., 2004). Detailed reservoir models were then built using the structurally restored horizons to create high resolution zones, facies distributions extracted from the model were then used to populate the model (Figure 9).

Digital data capture techniques and virtual model problems and pitfalls

The digital data capture techniques and related examples all have differing advantages and disadvantages (Table 1) depending on aim, outcrop size, fieldwork time, etc. The important aim is to integrate the data from the different techniques. Digital aerial photogrammetry, for example, generates local to regional-scale DTMs that can be analyzed remotely to map key stratigraphic horizons or structural data but is relatively low resolution and cannot resolve near-

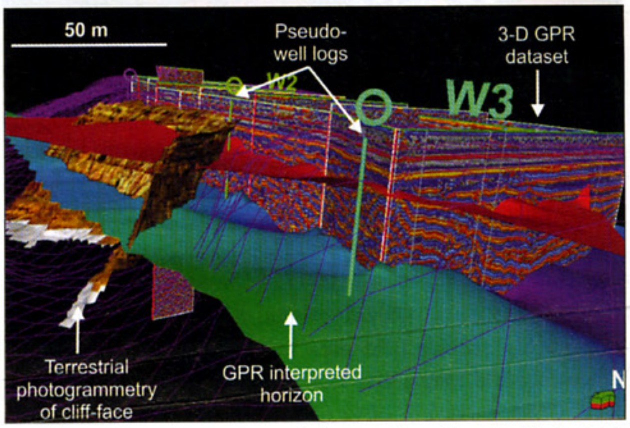

Figure 6 *Digital model of the Carboniferous Shale Grit Formation at Alport Castles, Derbyshire, UK. A turbidite sedimentary succession of sheet-like and channel-fill sandstone geometries were traced in 3D. Model input data included aerial (grid) and terrestrial photogrammetric output, 3D GPR dataset and interpreted horizons, sedimentary logs, photopanel interpretations and conventional surveying coordinates. Adapted from Pringle et al., (2004b).*

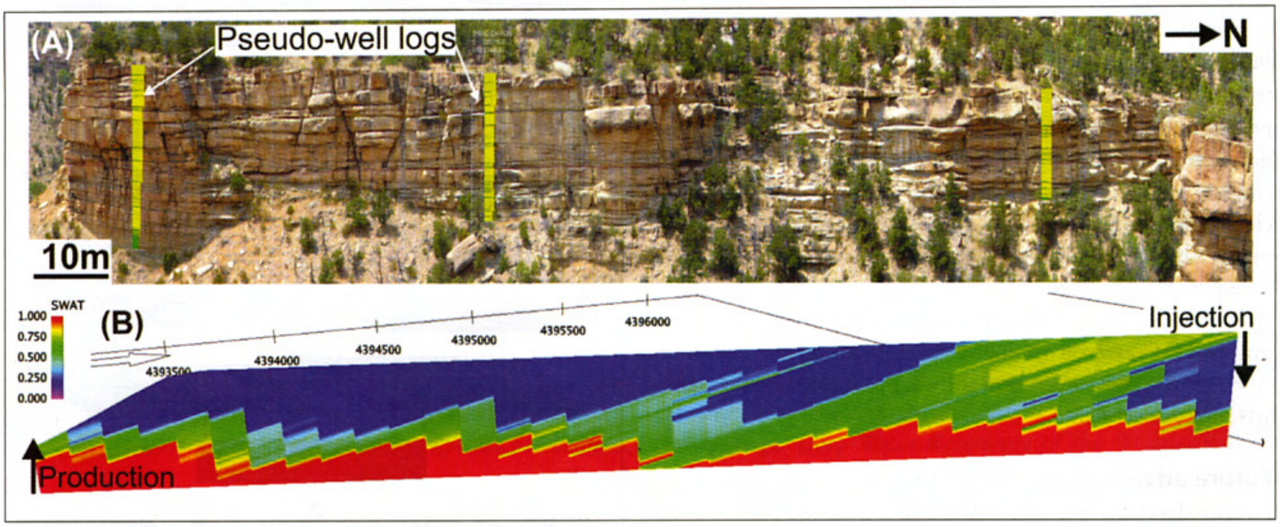

Figure 7 *Outcrop and flow-simulated reservoir model from the Panther Tongue, Book Cliffs, Utah, USA. (A) View of a 25m thick deltaic sandbody with southward-dipping clinoforms. Pseudo-well logs are used as input for reservoir model. (B) Cross section through flow simulated, 3D reservoir model showing water saturation after 10 years of injection and production. Note how clinoforms control the reservoir flow. Models such as this provide an important link between the reservoir engineer and the geologist and allow the investigation of effects of deterministically mapped sandbody architecture on fluid flow (Howell et al., in press).*

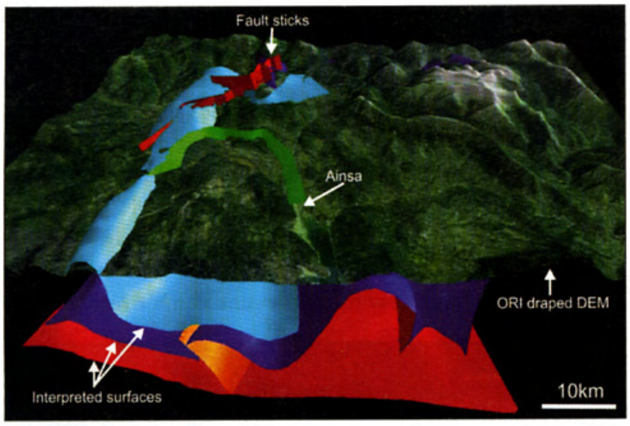

Figure 8 *Aerial photogrammetric output from the Eocene Ainsa turbidite system in Northern Spain has been integrated with conventional geological information, then interpreted for key stratigraphic horizons and structural data (see Fernandez et al., 2004 for more details).*

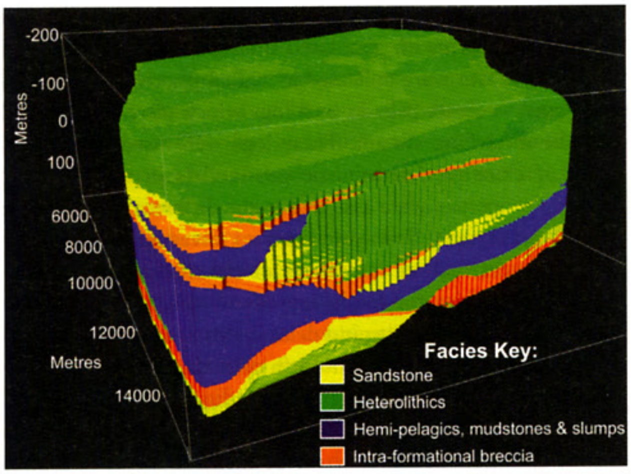

Figure 9 *Digital model shown in Figure 8 has been structurally restored and a high-resolution, 3D reservoir model created using Ainsa outcrop-derived sedimentary geostatistics.*

vertical cliff-faces. Digital ground-based photogrammetry can quickly acquire field data but requires significant data processing and may suffer from edge distortion effects. Field RTK dGPS surveying of key surfaces can be very useful in both ground-truthing photogrammetric surfaces and detailed outcrop study, but requires significant processing time and cannot be obtained from near-vertical cliff-faces or where there is poor overhead satellite coverage. Conventional surveying can obtain accurate cliff-face data but is slow to manually acquire. Ground-based LIDAR surveys very rapidly acquire accurate and dense site datapoint clouds, but the sizes of resulting datasets cause difficulty in processing, visualisation and data extraction.

Significant time can be spent creating virtual models from field or remotely acquired data, but this effort is redundant if the resulting models are not at the required resolution for the project objectives. Virtual models are only as accurate as input data, often significant fieldwork time is needed to generate a realistic model. If mm resolution is required, then perhaps a close-range, ground-based LIDAR survey should be embarked upon. Alternatively if only metre-scale geometric information is required, then perhaps a photopanel interpretation method would suffice. Virtual models should be used as an aid to improve the reservoir geologists interpretation, not replace it. Also, certain data integration software can only visualise datasets, not extract data.

Future advances and challenges

Further developments of computer and field equipment, computing hardware and software will have a tremendous impact on both reservoir scale and outcrop scale data capture. As technology progresses, 3D field-acquired data will become routinely acquired. RTK dGPS surveying systems will become ever more accurate, robust and allow direct downloads to remote PCs for real-time data processing. LIDAR rapid-scan surveying equipment will also become lighter and adapted for fieldwork, with development of semi-automated lithology classification software. Software development will simplify direct digital data import and analysis. GPR equipment development should greatly speed up outcrop data acquisition and data processing, allowing routine near-surface data integration to create fully 3D datasets (Figure 10). Once multiple outcrop datasets are merged to basin-scale models, these can be directly compared to reservoir datasets to provide more valid data to be used for reservoir modelling uncertainty studies (Figure 10). Outcrop

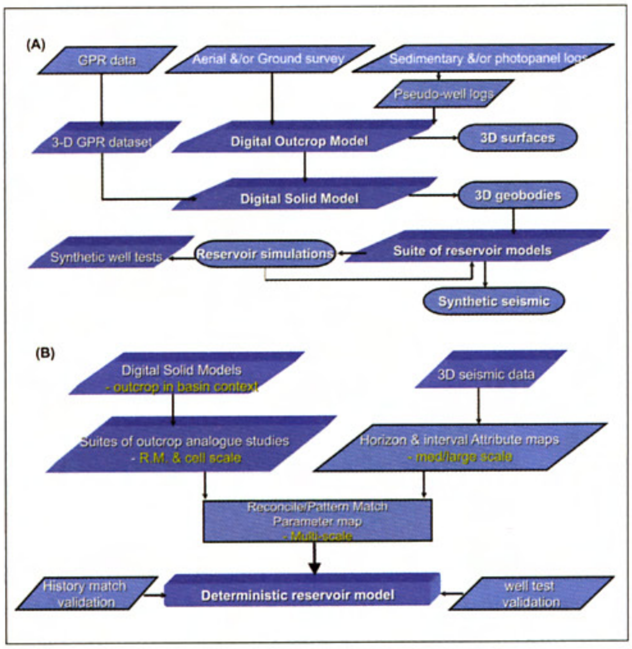

Figure 10 *Generalised workflows showing (A) steps taken to create and interrogate virtual outcrop models with (B) projected workflow to compare multiple outcrop analogue models with seismic data to reduce reservoir model uncertainty.*

analogue multipoint geostatistics will become required, changing current analogue study approaches. 3D seismic data will become increasingly able to resolve both intervals that may approach coarse outcrop-scale resolution and to define object shapes – ultimately this will aid future outcrop studies and refine the suitability of outcrops as analogues. As the petroleum industry becomes better able to forward model and design at basin-scale, onshore outcrop analogues or laterally-equivalent facies and offshore reservoir models should become ever more closely integrated. As with all analogue studies, the importance is of both acquiring optimal resolution of data necessary for the resulting model and using the correct analogue.

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