INTEGRATION OF TERRESTRIAL LASER SCANNING, DIGITAL PHOTOGRAMMETRY AND GEOSTATISTICAL METHODS FOR HIGH-RESOLUTION MODELLING OF GEOLOGICAL OUTCROPS

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ABSTRACT:

Like many fields in the earth sciences, geology is a rapidly expanding application area demanding spatial information, brought about mainly by the recent advances in geomatics technology. One area of high interest is the study of sedimentary rock outcrops, which can be used as direct analogues for the configurations of producing oil and gas fields in the subsurface. Such outcrop analogues are exposed areas of rock, ideally with strong three-dimensional properties, such as river-cut canyons or quarries, where it is possible for the geologist to study systems that are geometrically comparable to hydrocarbon-bearing rocks. As hydrocarbon reservoirs are typically inaccessible, spatial data are scarce, typically restricted to low resolution seismic surveys and a very limited number of boreholes. This makes the study of such systems problematic, and the application of outcrop analogues has long been used to infer much of the missing detail. However, in the past, spatial data acquisition techniques have been relatively crude, meaning that geological models and interpretation have been lacking in geometric detail and accuracy. Advances made to digital photogrammetry and terrestrial laser scanning have made geologists more aware of the potential of geomatics, and this is beginning to have an influence on such analogue studies. This paper therefore explores this new application field, and highlights many of the modelling tasks that are intrinsically linked to spatial information science. Terrestrial laser scanning and photogrammetry were used to capture detailed point clouds and imagery of outcrops, which were processed to form textured digital surface models. From these high-resolution, high-accuracy datasets, geological features were extracted, which form the basis for building geo-cellular models comparable to those used to model subsurface reservoirs, allowing direct comparison between the outcrop and the subsurface.

1. INTRODUCTION

1.1 Background

Geology is one of many application fields that require spatial information, and recent advances to geomatics technology and techniques are filtering through to create new opportunities for carrying out studies at far greater detail, and with higher accuracy than previously possible. An area of high relevance is petroleum geology, where the processes and materials related to petroleum bearing rocks are studied with the aim of improving the efficiency of extraction, as well as more easily being able to predict the location of new petroleum fields. Existing subsurface hydrocarbon reservoirs are typically modelled within a computer environment, bringing together all aspects of data and information on the field – from qualitative information on the types of rocks existing in the field to quantitative geometrical data derived from seismic surveys and well logs (e.g. Pringle et al., 2006). The geo-cellular reservoir model combines geometric data and geostatistical methods to build up a three-dimensional volumetric representation of the subsurface, which is then filled with petrophysical properties, such as porosity and permeability. In this way, the 3D volumes are used to predict the flow of fluids such as oil, water and gas through the reservoir. Of special interest is the distribution of barriers to fluid flow, such as faults and cemented beds. Understanding these can lead to understanding of how the field can most efficiently be produced (i.e. finding the best locations for producing wells).

Significant challenges exist in this procedure, not least because petroleum fields are often located kilometres under the earth's surface – often offshore – and are inaccessible for direct observation. In such settings, two main data types are commonly utilised: seismic data which provide spatial and surface information with a very low resolution (typically 20 – 50 m vertically), and boreholes which are extremely expensive (c. $25m in the North Sea). Boreholes provide excellent 1D sections through the reservoir but are widely spaced (typically less than 1/ km²). The availability of data is therefore limited, despite the fact that a good understanding of the underlying geology is critical to accurate reservoir modelling.

This paper illustrates the concept of using outcrop analogues to study similar geological configurations as producing fields, but in areas accessible for study. The use of terrestrial laser scanning and photogrammetry to capture and process high-resolution terrain models is outlined, as well as the means for integrating these techniques into the reservoir modelling workflow.

1.2 Outcrop Analogues

An alternative means of studying subsurface reservoirs is by using outcrop analogues. An outcrop analogue is an exposed area of rock with strong three-dimensional properties, such as a cut river canyon or quarry, which offers geologists the chance

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to study the spatial and geometric aspects of systems that are similar to those found in a particular subsurface field. Reservoirs primarily occur in sedimentary rocks which may be clastic (comprised of eroded and redeposited sediments) or carbonate (built-up of calcium carbonate based organic matter, e.g. reefs or shell banks). A good outcrop analogue is one that has been typically deposited under similar environmental conditions (such as in a river or on a beach) and has undergone a similar geological history to the reservoir that is being studied. Note that as they are at the surface, the analogues rarely contain petroleum (Figure 1). In addition, scale equivalence and good exposure are also required (Pringle et al., 2006). Using the outcrop analogue, the geologist can make observations on the rock types and properties, such as grain size, porosity and fossil content, as well as measuring geometrical characteristics, for example layer thicknesses and the locations of post-depositional features such as faults. These spatial attributes are extremely important in reservoir modelling, as the thicknesses of reservoir rocks (i.e. the rocks containing oil and gas trapped within their pores) determine the potential amount of petroleum, and the correct understanding of the distribution of barriers (e.g. shale layers and faults) helps determines the potential flow. The outcrop may be modelled as if it was petroleum bearing, with results relevant to the actual inaccessible reservoirs.

Figure 1. Sedimentary rock outcrop: Woodside Canyon, Utah, USA, showing exposed layers in a cut river canyon (approx. width 300 m). One correlated sandstone layer is marked.

In the past, spatial measurement has been very crude, using calibrated staves and tapes to record the thickness of layers in the outcrop. An important concept is that of the sedimentary log, whereby a vertical line through the outcrop stratigraphy (layers) is chosen. The geologist traverses this line as closely as possible, recording the rock characteristics and measuring the thicknesses of each bed (layer). By carrying out a number of such logs over the extent of the outcrop area, a picture can be built up of how the layers change and interact in space and time. Comparable data are recorded from boreholes in subsurface fields. A key difference between the subsurface and the analogue is that the geologist can, to an extent, see between the disparate points to fill in the gaps, whereas in the subsurface such logs can only be interpolated or extrapolated.

Because of the nature of eroded or quarried outcrops, high relief is often present, making access to the outcrop difficult. In these situations, spatial measurement could only be estimated from non-metric photography. An outcrop analogue may extend for many kilometres, and its often possible to trace the same stratigraphic layers for significant distance. A common problem may also be that the outcrop is discontinuous, disappearing because of poor exposure, vegetation, or erosion. In this case it has in the past been difficult to accurately relate the disparate log data, as without a common reference coordinate system, all geometry is relative, and unable to be linked together. Introduction of the Global Positioning System (GPS) has countered this problem to an extent, as log measurements can be located using handheld systems. However, general positional accuracy has been low, resulting in undefined error propagating into the final outcrop models.

2. GEOMATICS IN OUTCROP STUDIES

Advances made to spatial measurement technology offer high potential for improving the spatial resolution and accuracy of outcrop analogue studies, as well as improving the general accuracy of reservoir models. Specifically, the non-contact techniques of photogrammetry and laser scanning are of most interest – the high metric precisions of the techniques combined with the ability to achieve measurement on inaccessible, near-vertical surfaces allowing new opportunities in terms of data collection.

Use of geomatics techniques for outcrop analogues is not new, though examples are not common. Stafleu et al. (1996) acquired photogrammetric stereopairs of carbonate rock outcrops, which were processed to form digital elevation models (DEMs). These were then linked with petrophysical measurements with the aim of identifying a relationship between erosion and rock impedance. Adams et al. (2005) used real-time kinematic GPS and a reflectorless total station for recording 3D datapoints representing the outcrop surface. These were combined with a DEM created from aerial photogrammetry to form the basis for a reservoir model. Other examples (e.g. Bryant et al., 2000; Pringle et al., 2004) show that the use of spatial information in outcrop modelling is gradually increasing. However, it is the introduction of terrestrial laser scanning that is having an effect on how this application area is developing, probably explained by the relative ease of data collection, and the visually impressive results. A particular advantage is that surface models are likely to be of higher accuracy, due to the active laser system rather than the reliance on matching correlation that is an issue with terrestrial photogrammetry and high levels of relief (Baltasavias et al., 2001).

Slob et al. (2002) used multiple scans for creating a DEM for identifying surface discontinuities, by conducting gradient-based classification. Bellian et al. (2005) outline the usefulness of terrestrial laser scanning combined with digital photography for producing textured outcrop models that can be used for visualisation and training. Generally, the advantages conferred by laser scanning are becoming accepted within this field, though as yet, very little has been published other than 'state of the art' papers describing the potential of the technology (e.g. McCaffrey et al., 2005). Indeed, there are still few articles available where scanning has been used to enhance existing workflows. The following sections therefore develop a workflow for using geomatics techniques for reservoir modelling – from data collection to final model production and interpretation.

3. DEVELOPMENT CRITERIA

The criteria for outcrop modelling can be expressed as follows:

- Near-continuous coverage;
- Correctly orientated in a single coordinate system;
- Sufficient accuracy;
- High enough spatial resolution to capture the smallest features being studied;
- Complemented with high-resolution image data;
- Speed and efficiency.

Because the outcrop may cover a large area (of several square kilometres or more), there may often be discontinuities preventing complete coverage. This makes the use of a single project coordinate system essential, which is most easily realised using a GPS reference system and Cartesian realisation (such as the Universal Transverse Mercator (UTM) projection). Although having a global or national system is not essential, being able to easily tie in other data, such as logs or ground-penetrating radar (GPR) data, is an advantage. Where possible, continuous coverage of the outcrop is required, as this allows features to be more easily tracked. Where many layers are present, such as found in sedimentary systems, it is often the case that the only way to track layers correctly in the outcrop is by following the layer by eye (or in photography). If coverage is not continuous, it may be difficult to correlate or trace a bed with certainty (Figure 2).

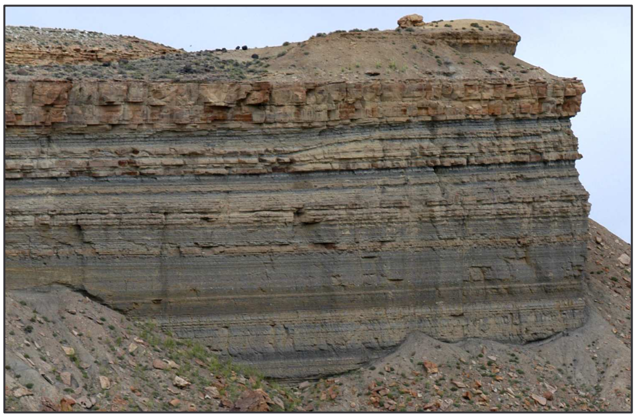

Figure 2. Detail of outcrop (Ferron member, Utah, USA), showing multiple sedimentary layers. Being able to track these features over large distances and from one face to the next is essential.

4. WORKFLOW DEVELOPMENT

4.1 Data Collection Techniques

Based on the criteria outlined above, terrestrial laser scanning integrated with photogrammetry and GPS was chosen as the most suitable means of collecting high-resolution, high-accuracy outcrop data. Although close-range photogrammetry alone could have been used, the complexities of data collection for the large areas required would have been inefficient and time-consuming. As the well-exposed outcrops are often in arid and remote environments, a logistical requirement is to be able to efficiently collect data in limited time periods.

Laser scanning meets the criteria of high data capture rates, high accuracy, resolution and efficiency. However, a disadvantage of laser scanning is the difficulty in identifying features within the cloud of points, even with colouring based on the intensity of the laser return (Axelsson, 1999). Because the identification of features is the most important aspect of this application, high-resolution digital imagery is therefore captured at the same time as the scan data – the greater resolution of the image data allowing continuous coverage of the required features. The complementary nature of the two techniques is now well-documented, and is the chosen route of a number of equipment manufacturers (e.g. Riegl, 2006). Finally, GPS is used to position the acquired scan data in a repeatable coordinate system.

In this research, a Riegl LMS-Z420i scanner has been used to collect datasets from a number of different outcrop areas, with different geological backgrounds and interest features. The aim has been to build up a ‘database’ of outcrop analogues for use in reservoir modelling research and education. The wide variety of geological settings and disparate project needs also require new, project-driven solutions to be developed. It is beyond the scope of this paper to give details on specific projects; instead, the general approach is outlined.

The LMS-Z420i scanner is used to acquire detailed point clouds of the outcrop analogues. A Nikon D100 can be mounted on top of the scanner, in a calibrated orientation relative to the scanner centre, allowing acquired imagery to be instantly registered in the project coordinate system (Figure 3). Imagery can also be acquired separately and registered later using tiepoints between the scan and image data. Calibrated Nikkor prime 50 mm and 85 mm lenses have been mainly used during image acquisition, as the range to the outcrops usually requires longer focal lengths to maintain the level of image detail required to identify necessary features. A single frequency GPS antenna is mounted above the camera, at a known offset from the scanner centre, and coincident with the *Z* axis of the scanner. The receiver records data for the duration of the scan setup and is post-processed relative to a nearby base station.

Figure 3. Riegl LMS-Z420i scanner.

Overlapping scans are captured over the extent of the outcrop. Because of the nature of the topography (often canyons, quarries, cliff faces), much redundant data ensues, and this is utilised in the registration of the scans to a single coordinate system. An iterative closest point (ICP)-based surface matching algorithm is used to carry out this procedure (Besl and McKay, 1992), and the resulting registered positions are transformed to the GPS system using the scanner centre points.

This gives the optimum solution for the registration problem, and is efficient in terms of data collection time in the field, as long as it is recognised that sufficient overlap must be captured (normally greater than 30%).

4.2 Processing and Accuracy Requirements

The primary processing product of this application is the creation of meshes from the overlapping point clouds. These are then rendered with the digital imagery to form realistic digital representations of the outcrop, allowing interpretation to be carried out (Figure 4). Another use of such models is for training purposes, allowing geologists to become acquainted with an area prior to fieldwork, in a more direct manner than just using two-dimensional photographs and maps. Features on the virtual outcrop models can be digitised directly by a geologist, with very little training, and with much higher accuracy than previously achievable.

Figure 4. Virtual outcrop model – Woodside Canyon, Utah.

Accuracy requirements for such outcrop applications are dependent on the scale of the features of interest. Often, the main interest is extracting the boundary between the different sediment layers across the outcrop's extent – usually metre-thick surfaces over several kilometres. The most important requirement is therefore the relative accuracy of the scan positions (ensuring the project is located in a single coordinate system), so that a surface layer digitised on one part of the outcrop model can be linked to the same layer in a different (and possibly unconnected) part of the dataset. Generally, the accuracy criteria for the models themselves are less important than for high-precision applications such as engineering or heritage recording. The outcrop surface is affected by erosion, which makes the actual topography a less important characteristic than being able to determine the point coordinates of the interest features.

Use of terrestrial laser scanning can easily result in very large datasets, and the use of every point to form a surface model is impractical and often unrealistic given computing power available. Decimation of the point clouds to reduce points in unwanted areas is a desirable processing step. However, it is ironic that because of the verticality of the outcrop faces, it is often the smoothest surfaces that are of most interest (as shown in Figure 2), so care must be taken in any implementation of a gradient-based point or mesh thinning algorithm. This highlights the point above: that the local topography is not the most important part of the accuracy requirement, as it can be thought of almost as a two-dimensional slice through the subsurface.

Despite this, the scale of the application determines how the outcrop is modelled. If small-scale features (such as fractures or deposition features) are to be captured in detail, these must be modelled using the raw data. The workflow is flexible enough to make use of all parts of the input to suit the application at hand. The raw point cloud can be used, a mesh at a suitable level of detail can be created, and the high-resolution imagery exists as additional metric data.

4.3 Preparation of Reservoir Modelling Data

Once scan and image data have been collected, and mesh surface models have been formed, interpretation and digitising can take place to define input data for reservoir model building. The aim of reservoir modelling is to build up a representation of the subsurface based on geostatistical operations performed on available input data and information. A three-dimensional recreation of the geometry of the stratigraphy is performed, based on the interpretation of the geology. Use of an outcrop analogue allows constraints on the geometry that may be unavailable with true subsurface reservoirs. However, the outcrop still only allows constraint from the exposed areas, and interpolation and extrapolation must be carried out in the remainder of the area. This is reduced, but not removed, by having good three-dimensional exposure.

Geometry interpreted from the scan and image data are used as the constraints for the reservoir model. Three-dimensional lines are measured directly on the textured surface models or, if high-resolution is required (due to hardware limiting the size of textured models that can be displayed), directly on to the imagery. Single-ray back projection is used to determine the object-space coordinates of the image points using a DEM derived from the scan data (Zhou and Fraser, 2000).

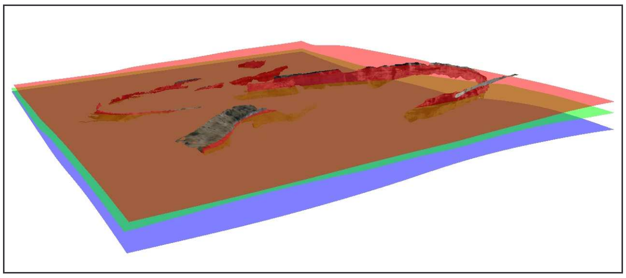

Figure 5. Geology surfaces derived from lines measured directly on textured outcrop models of a river bend.

Measuring lines, or even points, representing the same geological surface across different areas of the outcrop (for example on multiple arms of a river-cut canyon) allows the three-dimensional geometry of the surface to be recreated. This requires the use of interpolation techniques to form a surface from the measured lines. Many interpolation algorithms exist (e.g. Isaaks and Srivastava, 1989); however, because of the relative sparseness of the lines with respect to the whole area, it is important that the technique and parameters are chosen to ensure fitting of the interpolated surface with the input data, and that the resultant surfaces are geologically plausible. From the line input, a grid surface is interpolated between the lines, and extrapolated beyond, based on the interpretation by the geologist. Testing the effects of different interpolation techniques is a possible future research topic; however, comparing the differences between the input lines and the resulting geology surface allows some quantification of the accuracy of the fit. Performing this interpolation stage for line sets corresponding to each geology surface results in a number of grid DEMs for input to further reservoir modelling (Figure 5).

The surfaces derived from digitised lines are used to define zones that can be filled with an irregular cellular grid. Properties assigned to the cells of this grid are used to populate the volume with properties such as different rock types. Such a volume is the digital representation of the true subsurface, with observed data in the form of the outcrop spatial data plus data recorded by the geologist (such as sedimentary logs), and extrapolation based on the interpretation of the geologist. It is also possible to combine data from behind the outcrop exposure, such as drilled cores or GPR, to add further constraints to the volume building process (e.g. Pringle et al., 2004). Cells in the 3D grid volume are represented by corner coordinates and additional properties such as rock type and porosity (Figure 6). The shape of the cells is normally irregular, although the grid columns are typically vertical. An irregular, eight corner point grid is desirable, as it is likely to conform better to the geology. Because a model may cover a large area, the number of cells in a reservoir model may be enormous, in the same manner as a grid DEM but with an additional third dimension. To streamline the models and save memory costs, the 3D grids are often designed with a very large *X* and *Y* spacing, with *Z* much smaller (commonly 100 x 100 x 1 m). This represents the fact that in most sedimentary systems, the properties are heterogeneous in the *X* and *Y* direction, because of near-horizontal layering, and it is the resolution in the *Z* direction that needs to be captured with higher resolution. Adaptive gridding with irregular corner points is therefore used to efficiently control the volume, in the same way that DEMs are adaptively reduced to account for topographic roughness.

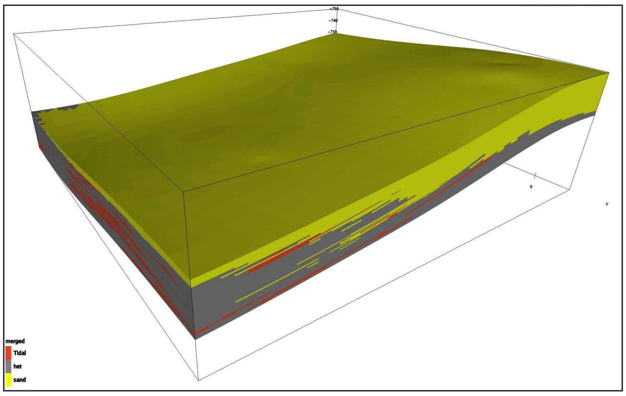

Figure 6. 3D grid volume populated with rock deposition types having variable flow properties.

Grid volumes must also take into account faults – discontinuities in the rocks caused by the differential movement of the various layers. These geological breaklines must be modelled in the 3D volume in the same way that conventional breaklines are used to refine DEMs. Faults can also be extracted from the combination of scan and image data, and input as lines or polygons to the modelling software. The fault is then converted to a three-dimensional surface, in the same way as described previously (Figure 7). The fault is then used to constrain the geology surfaces and the 3D grid volumes.

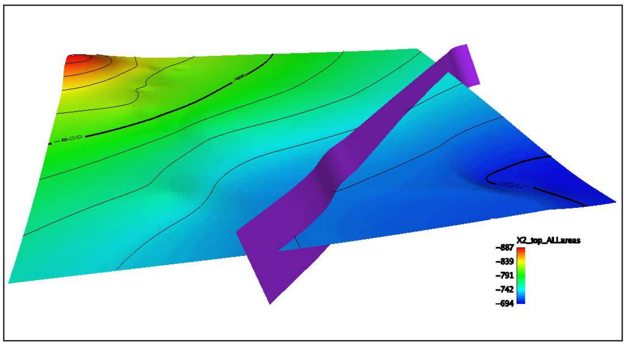

Figure 7. Fault surface (purple) and geology surface (x2 vertical exaggeration).

Once the reservoir model has been created, based on the scan and image data, as well as conventional geological data and interpretation, it then offers a number of important uses:

- Visualisation of the outcrop subsurface;
- Improved 3D understanding of the depositional type distribution and geometry of the reservoir;
- Calculation of volumetric data;
- Estimation of the uncertainty/error in the model;
- Simulation of fluid flow;
- Upscaling of analogue data to improve understanding of existing petroleum reservoirs.

5. QUALITY CONTROL AND UNCERTAINTY

From this brief discussion of modelling analogue outcrops, it can be seen that there is high potential for errors to exist and propagate throughout the workflow. This is to an extent unavoidable, and is inherent in the nature of the application: modelling a 3D volume using only a subset of the area that is accessible for study. The aim of this work is a general improvement in modelling techniques by using accurate spatial data, whilst minimising the error sources at each processing stage to minimise the overall uncertainty in the reservoir model. In the past, with only approximations of geometric information taken at discrete intervals, during sedimentary logging, undefined error could be introduced to the extrapolation of geology surfaces. This in turn would result in further error when a 3D grid was made, affecting the geometry of the resulting model, any volumetric calculations made, and fluid flow simulations.

Modelling of the outcrop geometry using terrestrial laser scanning gives far better constraints on the available outcrop exposure. The '2D slice' through the subsurface can be defined with high accuracy, and the stratigraphic layers can be followed continuously, instead of only sampled at discrete intervals. This in turn means that the geology surfaces are likely to be defined with higher accuracy, giving rise to more accurate reservoir models. At each stage of the workflow the accuracy can be checked with the raw geometry data – by checking the derived terrain model with the raw point cloud, by comparing the digitised line segments with the image and geometry data, by analysing the interpolated geology surfaces to check they correspond to the correct positions within the scan and image data – to name just a few. Such quantification of the error gives confidence to later stages of processing.

6. CONCLUSIONS

A new application for spatial information science has been addressed: that of modelling geological outcrops. Because of the recent introduction of terrestrial laser scanning and digital photogrammetry to the field of petroleum reservoir modelling, interest is high, and is likely to increase in the coming years. It can be concluded that the integration of laser scanning and photogrammetry confers the following advantages to the application area:

- Increased accuracy throughout the workflow;
- Increased resolution of spatial sampling;
- Continuous coverage – the ability to resolve fine geometrical detail of bodies over wide areas;
- Coverage of inaccessible areas, such as vertical cliffs;
- Increased awareness of error propagation;
- Improved accuracy of geological surface definition;
- Ease of repeatability through linkage to GPS reference system;
- Integration of additional data (such as GPR, seismic) is facilitated, and much more feasible.

However, despite these improvements to the modelling flowline, the introduction of more accurate spatial data is not an umbrella solution that will solve every problem. Conventional geological fieldwork is still essential to gain an understanding of the deposition processes, and a wider insight into the potential and limitations of spatial data is required by geologists before the two fields can be more seamlessly integrated.

There are many avenues to follow for future research into the use of terrestrial laser scanning and photogrammetry for outcrop analogue modelling. In particular, the use of image data has so far been limited to providing textures for the DEMs and for manually defining features. More work will be carried out on the database of outcrops that has now been collected to give improved understanding of these field areas.

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